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First Edition

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Welcome to Dayton!

It is with great pleasure that I personally welcome you to the 2015 AMSAT Annual Meeting and Space Symposium. This is the 33rd Space Symposium, reflecting a long tradition (started in the early 1980's) to provide an annual forum for amateur satellite enthusiasts to gather and share their ideas. AMSAT is proud of the technical content of the papers presented over the years reflecting the inventiveness of our volunteers and the significant contribution of presenters to "advancing the radio art."

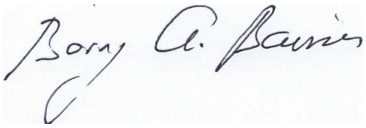
Holding our Symposium at Dayton this year is certainly fitting given that Dayton is known as "The birthplace of Aviation" while AMSAT now embarks on a new era for amateur radio in space. Fox-1A is scheduled to fly this month as part of ELaNA-XII followed by Fox-1Cliff and Fox-1D in first quarter 2016 on a commercial launch vehicle, while RadFxSat/Fox-1B is currently scheduled to fly in November 2016 as part of ELaNa-XIV, or four Fox-1 series spacecraft launch in 14 months! While based upon a standard design utilizing a robust (for a 1U cubesat) communications package, each spacecraft has its own unique personality, ranging from differences in scientific payloads to differences in spacecraft capabilities (such as the addition of a new MPPT module) to variations in amateur radio capability (Fox-1Cliff and Fox-1D will feature a L-Band uplink receive capability) reflecting the evolution of a program that was initiated in 2009 and is now coming to fruition. The next 14 months will be rewarding ones for our volunteers, who spent countless hours designing, documenting, collaborating, fabricating, testing, and integrating our Fox-1 design into flight hardware. There is a significant sense of pride in completing spacecraft that will be used by amateurs, students, and scientists who will benefit from amateur radio capabilities on board, educational opportunities in the classroom, and the scientific data that will be available from payloads on board provided by university students and faculty.

As is AMSAT's tradition, this edition of the Proceedings contains details about the Fox-1 satellite design that we're placing in the public domain through formal publication. We're releasing these materials so that we may openly discuss our spacecraft development efforts in public as well as our desire to encourage greater use of amateur radio in space, and to provide a foundation for other institutions to utilize our design. "An OSCAR in every university cubesat" will enhance amateur radio's presence in space while supporting scientific payloads.

Meanwhile, the 33rd AMSAT Space Symposium provides an opportunity to discuss our next generation of projects. Earlier this year, AMSAT announced a collaboration with Virginia Tech that may provide opportunities for placement of an amateur payload in Geosynchronous Orbit as secondary payload and proposing the adaptation of the Phase-3E space frame to fly to a High Elliptical Orbit supporting both governmental and amateur radio payloads. I look forward to the discussions concerning these proposals as well.

After forty-six years, we continue to develop remarkable satellites with educational outreach and scientific benefit that provides the basis for fulfilling AMSAT's mission. Your support will help to ensure a bright future.

73,



Barry A. Baines, WD4ASW
President

Nick Lance, KC5KBO, passed away on May 24 in Houston, Texas at the age of 65. Nick was a member of the Amateur Radio on the International Space Station (ARISS) team, serving as the primary Amateur Radio license trainer for the ISS astronauts. Nick played an integral role in encouraging and training countless astronauts to pursue their Amateur Radio licenses and become active on ARISS. He also inspired and trained dozens of NASA aerospace education specialists to get their ham tickets and taught a 'Hamster' course to middle schoolers, inspiring them to pursue careers in technology through Amateur Radio and ARISS activities.

Nick grew up in New Jersey and held mechanical engineering degrees from the Georgia Institute of Technology and the University of Houston. He began his career as a co-op student at the Johnson Space Center in 1968. He went on to become part of the Apollo program and was involved in all of the manned spaceflight programs since Apollo. Nick contributed immensely to the development of engineering standards to fly our astronauts beyond low Earth orbit, to the Moon and Mars He retired in August 2009.

Nick was named ARRL Professional Educator of the Year in 2003, and was a member of the JSC Amateur Radio Club and past president of the Clear Lake Amateur Radio Club. Nick also competed on the tournament horseshoe circuit as a member of the National Horseshoe Pitchers Association, winning back-to-back gold medals in the 2009, 2011, and 2013 National Senior Olympic Games. In 2013 he also won the Texas State Horseshoe Championship.

Frank Bauer, KA3HDO, called Nick "a smart, caring, considerate, and helpful person" who loved Amateur Radio and said that he would miss Nick's quick wit and sense of humor.

Nick is survived by his wife Renee, KC5VMA and his children Erica, KC5KBP and Nick, KC5SWM.

DSP Hardware in AMSAT P4 Geosynch Ride-share

Rincon Research Team
Dr. Michael Parker, KT7D
John Wallace KE7QVC
John Forinash, N8NJD
John Jensen
Presentation at AMSAT General Meeting, October 2015

1. Background

This spring Mike Parker was approached by Bob McGwier about the possibility of Rincon Research Corp. donating a DSP-based radio as part of ride-share opportunity on an Air Force satellite destined for geosynchronous orbit. Rincon was building hardware known as LPFE (Low Power Front End) for terrestrial use and planning to extend this hardware to space applications.

Rincon's management quickly approved donation to get started of at least one LPFE and a $25K IRAD budget for preliminary work with AMSAT.

The purpose of this presentation is to describe:

1) How the LPFE fits into the rest of the package being developed by AMSAT
2) What the LPFE is (and isn't) capable of
3) How the LPFE operates in a terrestrial environment and changes necessary for space
4) Our concept of the development and test issues
5) The development/test facility currently interfaced to the internet at Rincon in Tucson and how it might be used

Figure 1 pictures the host satellite .

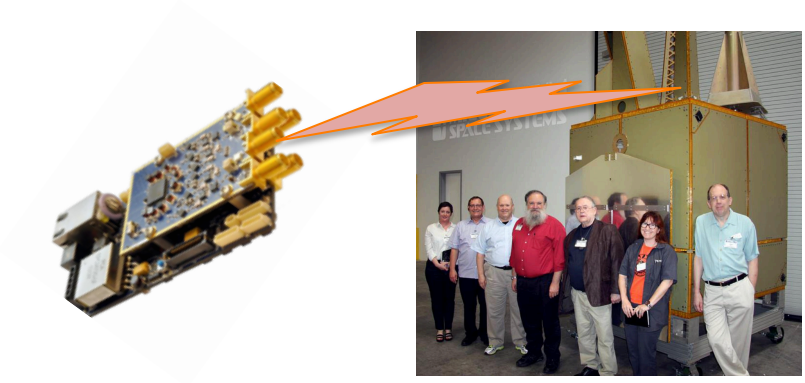


Figure 1: First meeting at Millennium Space Systems (MSS) showing a mockup of Air Force satellite which will carry a small AMSAT ride-share package. Rincon's Low-Power Front End (LPFE) is shown at left (terrestrial version, not to scale)

2. Payload

Figure 2 is a simplified concept of the AMSAT payload. Once the satellite is in geosynchronous orbit one side of the satellite will face earth. On this side will be mounted receive and transmit antennas. For purposes of this paper some assumptions have been made about the components that Rincon is not building. We have also left out the host spacecraft (which supplies power), the power supply of the AMSAT payload, etc. Frequencies illustrated are our current understanding.

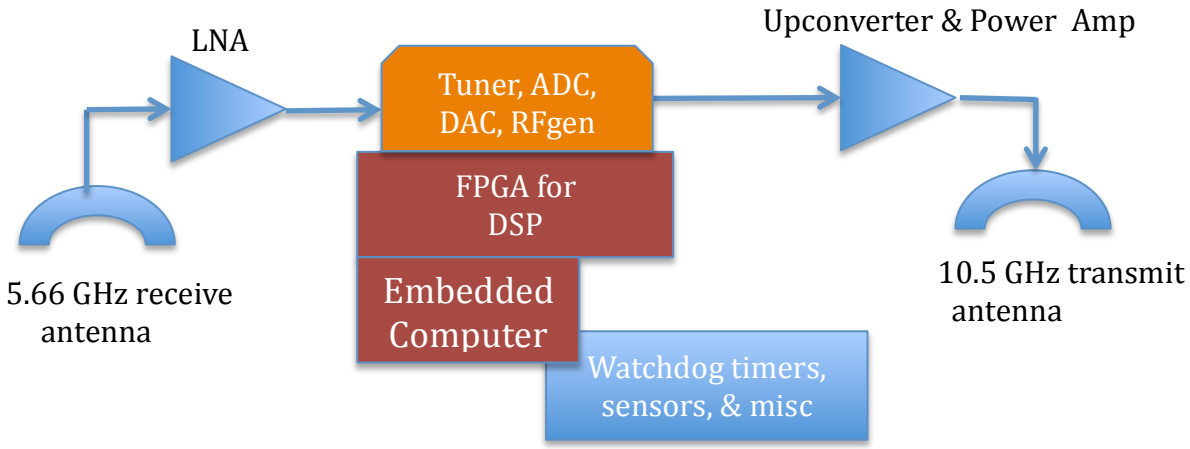


Figure 2: Simplified payload block diagram. Blue items are external to the LPFE DSP/Computer board. The LPFE board in brown and orange is Rincon supplied.

On the left of Figure 2 is the uplink antenna with a LNA setting the uplink noise figure that in turns feeds an amplified signal to the LPFE. The LPFE may be viewed performing three main functions.

1) RF to digital and digital to RF interface module. This uses the same Analog Devices chip as in the B200/B210 boards that some of you may own. It directly tunes the uplink frequency of 5.66 GHz, but the output will be at an IF frequency which must be externally upconverted to 10.5 GHz and amplified for transmit.
2) An FPGA fabric for performing heavy-lifting DSP such as tuners, demodulators, signal sources, etc. occupies part of a Zynq 7030 or 7045 Xilinx(R) system on a chip.
3) The same Zynq chip contains two ARM computer cores for performing general purpose computing functions. In the terrestrial LPFE a version of Linux running on the ARM controls the signal processing and provides a digital control interface with the outside world. AMSAT plans to also run software that monitors and controls their payload on the ARM. This will require close coordination and testing.

A final important item in the diagram is an external watchdog circuit to provide reset commands in the event that something goes wrong. More about that later.

3. LPFE Overview

The LPFE is an existing Rincon Research design that is being used in terrestrial applications. It is an evolution of our Mountain Brik Product line that usually operates interfaced to a control computer either directly or via an Ethernet. A photograph of a terrestrial LPFE is in Figure 3.

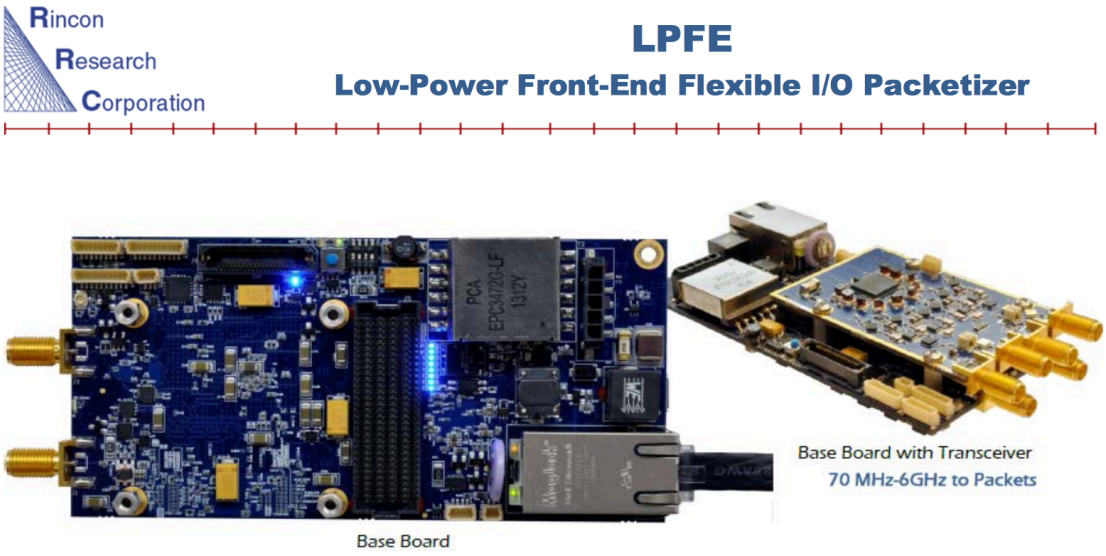


Figure 3: Photo of a terrestrial LPFE with mother board on left and combination with mounted daughterboard at right. Not shown on the reverse side is a Zynq 7030 (or 7045) system-on-a-chip. A conduction-cooled head sink removes heat from this and other hot chips.

Although schedules appear to be very tight, Rincon hopes to improve the board design for use by AMSAT. Planned modifications include:

1) Power supply more resistant to latch-up
2) Flash memory radiation resistant
3) Conduction cooling for attaching to spacecraft cold plate instead of air-cooled fins
4) The daughter card will be incorporated into the main card providing a single-card solution

Interfaces to AMSAT-provided watchdog circuits will probably be via existing connectors.

Major software changes are envisioned for the space version. These will be discussed later.

4. Schedule Drives Philosophy

Schedule is the thing that concerns Rincon the most. We understand that the AMSAT payload must be delivered to Millennium Space Systems for integration by July 2016. In order to meet this schedule, Rincon has adopted the philosophy of delivering only the absolute minimal functionality at integration with more to be supplied later. Remember the rule:

"If the minimum isn't good enough, it wouldn't be the minimum."

The goal is to have a rock solid and tested set of firmware/software ready for launch that allows us to load additional firmware/software once on orbit. This minimum capability must include features that allow us to test and control the payload. It might also include linear transponder functionality since it is relatively straightforward, but complicated digital communication protocols may have to wait. The plan is to develop and test additional functionality on system simulators while waiting for launch. This additional functionality will be loaded later.

If we have access to the payload before launch, we may be able to enhance the "launch load of firmware/software". But our baseline plan must be to load on orbit.

5. The Devil is in the Details

5.1 The Boot Process

It is useful to consider the details of the boot process because:

1) The system is dependent on fairly complicated software including a Linux operating system as well as applications code. If the system doesn't boot, the entire payload has failed.
2) Various failure scenarios can be envisioned ranging from radiation-induced malfunctions to control operator error. Various levels of system re-boot (including a cold start from the launch program) represent recovery modes.

The 1st stage of the boot process will start with the tested set of code stored in ROM before launch and then use it to load additional code after launch. This is the normal boot starting with power off, or it might be triggered by a watchdog timer expiring or by a command station reboot request.

It is possible that this 1st stage code stored in pre-launch ROM will get corrupted. Since functioning of the payload is dependent on the boot software being correct, one must pay careful attention to booting from an uncorrupted copy of the code.

One proposed plan is to store multiple "golden" copies of the code in ROM and use the RSA check function of the Zynq chip to verify validity of the code. If it fails, the next copy in sequence will be checked, etc. until a valid copy is found.

As mentioned, one function of the 1st stage boot is to allow 2nd stage boot code to be loaded into non-volatile RAM. If 2nd stage code is already present, a command from a control station might then select a specific application to boot in the 2nd stage. The validity of the software in the 2nd stage boot would be checked as before.

5.2 Functions at Launch

Table 1 represents our 1st cut at listing the minimum functions that must be present at launch.

- Power-up boot and various reset and recovery modes
- Telemetry downlink & beacon
  - Including command acknowledgement
  - Goal is to downlink spectral analysis or pre-D snapshot in telemetry for test, checkout, and monitoring
- Narrowband command uplink
  - High link margin reserved for command stations
  - Commands to change operating mode
- Payload comms uplink/downlink (wideband)
  - Reserved initial checkout, software updates, anomaly resolution, special monitoring
- Initial communications load
  - Minimum is linear transponder
  - Likely is several linear transponders with different bandwidths
- Stretch goals (unlikely unless can load after delivery or there is a slip)
  - Transmultiplexing Interference Canceler (TMIC) in transponders
  - On-board demodulators, switching, and multiplexing into single digital downlink

Table 1: First cut at functions which must be present at Launch (the minimum)

You will note that some of our (and your) favorite communications ideas didn't make the cut, except as "stretch goals". That's not because they aren't good ideas. It means that we will likely have time to do only part of what we ultimately want to do before the payload is frozen for launch.

That is why we are planning to load and demonstrate cool things once the spacecraft is on orbit. Suggestions and advice are solicited.

5.3 Spacecraft Software Development

Figure 4 illustrates the current test bed implemented at Rincon Research in Tucson to allow spacecraft software development to proceed. Immediate access to a LPFE is key to having any chance of meeting our schedule. For now Rincon IT staff is providing support to manage the Firewall and the Linux SSH server. We anticipate that AMSAT developers will want to control software and use of the Development Support Computer and LPFE. Suggestions and assistance are welcome.

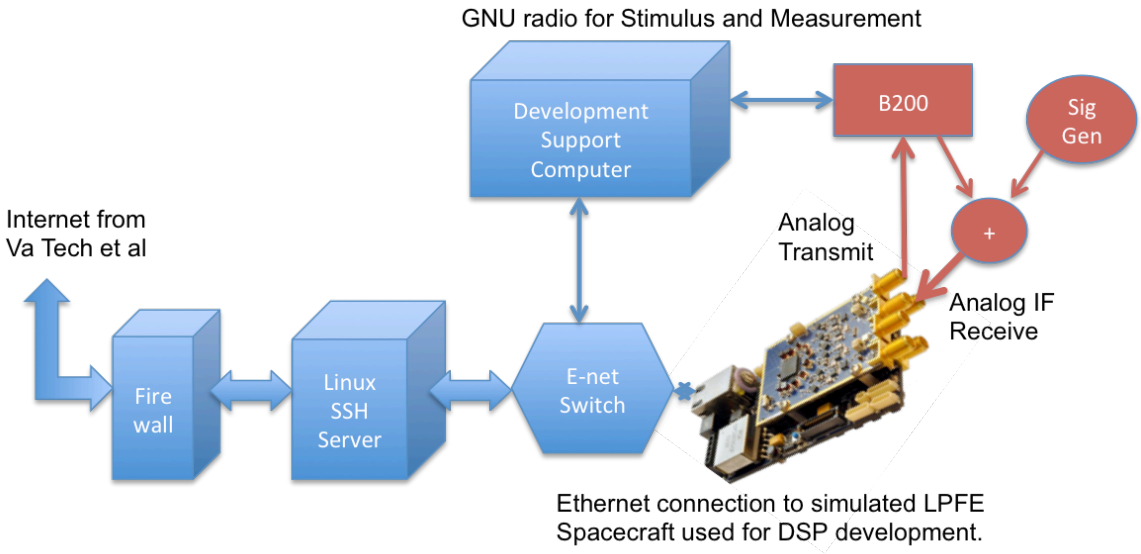


Figure 4: Block diagram of exiting Spacecraft Simulator test bed that allows remote login for spacecraft software development and testing. Rincon Research IT staff currently maintains the Firewall and the Linux SSH Server. Hard-core AMSAT developers can have immediate access.

This equipment is located in an area with controlled access. The area is air conditioned and has uninterruptable power. It is attached to the internet with 100 Mbps service shared with other Rincon traffic, but outside Rincon's company firewall. Placing other computers or devices on this AMSAT network is possible.

Rincon anticipates that AMSAT wishes to control who has access to the software that will be running on the payload, and that much development will be done at remote facilities. A Rincon-maintained firewall separates the internet from a SSH server dedicated to AMSAT. AMSAT personnel will be provided with access to the AMSAT local network by logging into the SSH server. AMSAT will be responsible for any additional computer security or procedures they deem advisable.

An additional computer is provided to assist with development. It is interfaced to a B200 board via USB. This computer will be controlled by AMSAT. It has two functions:

1) Assisting development of the LPFE spacecraft software by using the B200 board to generate stimulus and monitoring response. GNU radio may be used to do this.
2) Acting as a control station in concert with a B200 board.

The equipment and cabling marked in red carries RF signals for stimulating and monitoring the spacecraft simulated with the LPFE. Blue cables represent digital data paths (IP, Ethernet, and USB)

5.4 Possible Ground-Space Simulator

An extension of the Spacecraft Software Development described in the previous section is possible to form a complete Ground-Space Simulator. This would be implemented once we have working spacecraft code and is diagrammed in Figure 5. It assumes that B200 boards will be used for the ground ham stations. Four ground stations are represented by the B200 boards in the upper right of the slide. The 5.66 GHz output from these boards is combined in a summer with the output from a ground command station illustrated in the lower right. This is added to noise and perhaps interference from a signal generator and fed into the payload simulator.

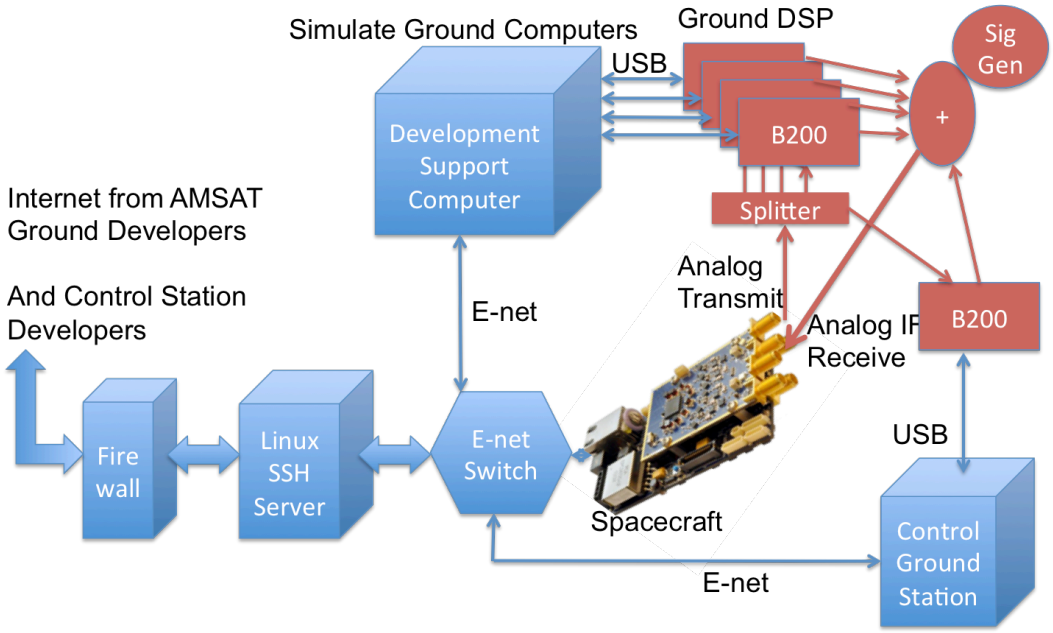


Figure 5: Extension of the Spacecraft Simulator to allow simulation and testing of the complete Ground-Space system including Ground Stations. This would occur once a working spacecraft simulator was complete.

The IF output from the satellite simulator is split and fed to the ground stations and to the command station. The simulator would operate at IF frequency without need for additional RF components to upconvert / downconvert to X-band. The diagram omits some components such as attenuators, noise sources, etc. that would be necessary for an accurate simulation.

We have also assumed that multiple copies of ground station software can be hosted in one computer. Otherwise, we would need a separate computer for each B200 board. You may also note that a Control Ground Station computer and its B200 board has also crept into the simulation. This is to somewhat separate Control Station functions from those of normal users.

This doesn't test RF paths and hardware like a "Ground Sat", but it allows AMSAT members across the country to participate in development of communication protocols while only tying up one spacecraft simulator.

5.5 More LPFE Details

This section will go into more details of the LPFE design.

5.5.1 RF and Analog-Digital Interface

A block diagram of the daughterboard that interfaces between the RF and digital worlds is in Figure 6. At the left of the diagram are two input and two output connectors. Between these connectors and the Analog Devices chip are switches, buffer amplifiers, and filters. The Analog Devices' Catalina– AD9361 chip performs direct RF to digital and digital to RF conversion. The many-pin connector at the right of the diagram communicates digital data, clock, and control to/from the motherboard.

It is worth noting that the inputs are paired and can only operate at the same tuned frequency. The outputs may be tuned to a different frequency than the inputs, but are also paired.

We note that Rincon also manufacturers a daughter board with multiple DACs and ADCs that offer advantages for certain applications involving IF frequencies up to about a GigaHertz. At the risk of adding complexity to the external RF hardware, this is an alternative should the Analog Devices chip not be sufficiently radiation tolerant

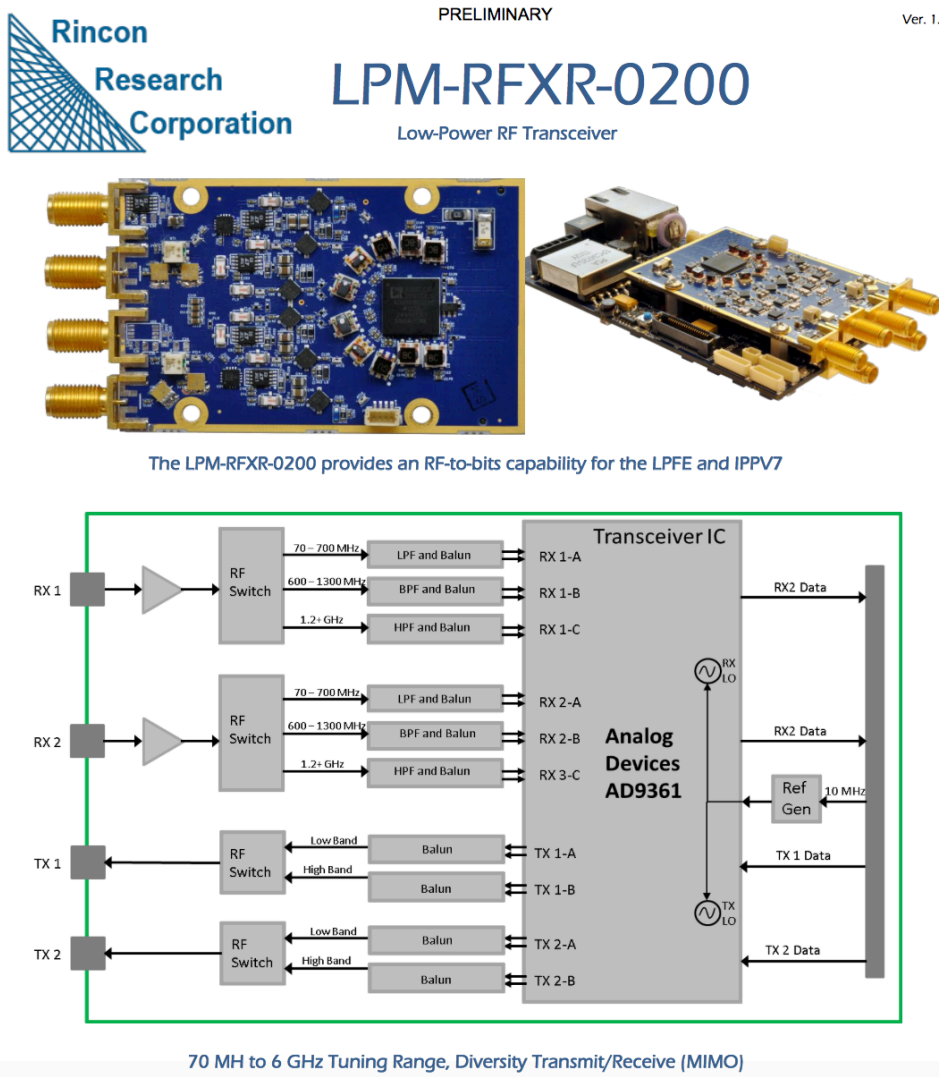


Figure 6: Picture and block diagram of RF Analog-Digital daughter board on terrestrial LPFE. This functionality will be integrated into the mother-board in the AMSAT design.

5.5.2 LPFE Mother Board Block Diagram

A diagram of the mother board shows the details of a LPFE motherboard. Input from the RF Analog-Digital daughter board arrives at the I/O Mezz. connector interfaces directly to the Zynq FPGA fabric.

You will note 8 Gb of DDR3 memory is available to the FPGA fabric and 4 Gb available to the Dual ARMs. An external interface is shown to an SD Card. An SD card is normally used for the power-up boot. This may be changed due to radiation considerations.

An Ethernet external connection is often used for terrestrial applications. In one application a user can remotely log into the LPFE via SSH through Linux running on

the ARMs. The same application provides a web server on the ARMs so that a remote application can control the LPFE and receive data and power spectra computed by the FPGA.

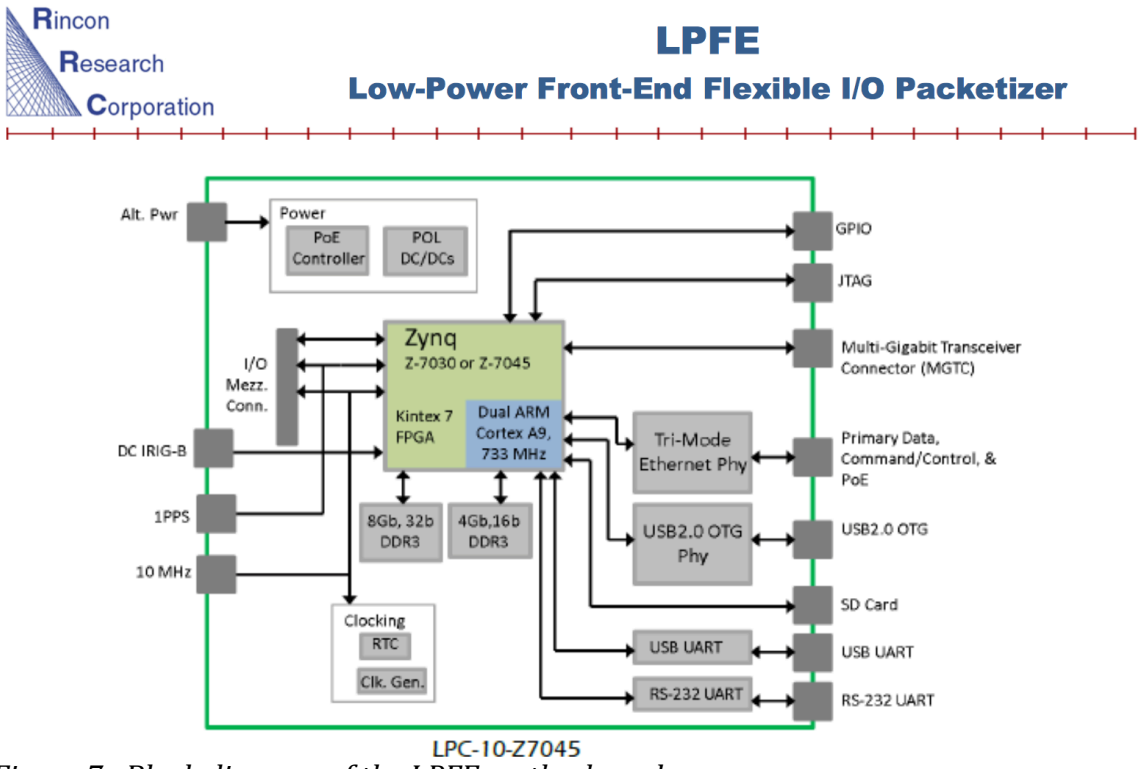


Figure 7: Block diagram of the LPFE motherboard

We will use the Ethernet connection during payload development, but once on orbit all commands, control, data, etc. must be transmitted over the RF ports. This represents a major software change inside the LPFE.

Additional external interfaces may be used during development, but presently have no function once on orbit.

5.5.3 What's a Zynq?

The LPFE incorporates several major functions.

1) An RF daughterboard that can transmit or receive between 70 MHz and 6,000 MHz. This is based on an Analog Devices Catalina chip on a Rincon-designed board. This converts analog bandwidths up to 56 MHz between analog and digital domains.
2) A processing board centered around a Zynq 7030 (or 7045) system on a chip. The heavy lifting of digital signal processing is done by the FPGA portion of the chip, and the ARM processor cores provide random logic and control. A Rincon-modified version of Arch Linux runs on the ARM processors.

Rincon typically develops the FPGA processing using VHDL. Wiring hardware functions is a foreign concept to software developers, and is very time consuming. We are monitoring alternative means of programming the FPGAs, but so far have not seen reason to disbelieve the old saying that one gets 10 times the performance with 10 times the programming effort.

We do believe that attempting to implement random logic in FPGA fabric, for example using a version of C, is a very bad idea. However, we continue to monitor concepts for stitching together pre-designed modules with higher-level code. Concepts like RFnoC or perhaps OpenCL on the FPGA are intriguing, If anyone thinks that is the best approach, we would be supportive. Perhaps we could learn something.

The Zynq family has undergone radiation tests and proved to be reasonably radiation tolerant when certain precautions are taken such as disabling cache memory.

5.5.4 Terrestrial Configuration of LPFE

There will be substantial differences between a space based and its terrestrial counterpart. I will start by describing operation of the terrestrial version and then describe changes that are contemplated for the Space LPFE.

The typical terrestrial LPFE is programmed to boot on power up and load a image from flash into RAM. Once the image, including Linux, is loaded, a Linux terminal interface is accessible from a local or remote terminal using the Linux SSH command (TCP/IP protocol) to log into the Linux running on the Zynq's ARM. Multiple applications have been designed to run on the LPFE. In one data capture application the ARM runs a web server which presents a graphical interface over the Ethernet to local or remote computers. In this application the ARM controls the RF tuner frequency, bandwidth, and gain through receipt of HTTP commands from the remote user's graphical interface. As an alternative, one can issue "curl" commands from the remote terminal to the web server.

Note that the above application has a mixture of data communication mechanisms ranging from one-way UDP packets whose delivery is not guaranteed to handshakes via TCP/IP While this was a good mixture for the particular application, it needs to be re-thought for the AMSAT mission. For example, sending commands that require 2-way TCP/IP handshakes before action is taken may not always be a good idea. Likewise, it is well-known that the standard TCP/IP protocol stack causes problems transferring data when encountering ¼ second round-trip delays to geosynchronous satellites.

5.5.5 Changes for Space

Rincon Research has identified changes to the terrestrial design for space use listed in Table 2.

- Hardware
  - External keep-alive reboots on failure or missing heartbeat signal
  - Radiation-tolerant power supplies
  - Radiation-tolerant ROM
  - Re-design conduction cooling
  - ECC memory (HW or SW ?)
  - Integrate two boards into one
- Software/firmware
  - Disable cache on microprocessors
  - Use Xilinix secure image function and sequence through multiple "gold" copies of boot if parity fails.
    - Perhaps enhance error detection and correction?
  - Possibly run a configuration memory scrubber
  - Reboot on kernel panics or other Linux error messages
- RF instead of Ethernet interface for command/control/data
- Add spacecraft control and monitoring function
  - RF power control
  - Communications mode control
  - LPFE power control
    - Full function, telemetry only (rest of FPGA off), sleep (microprocessor only), ALL OFF

Table 2: Desirable Changes to the Terrestrial LPFE for Space Use

A key hardware item that we expect AMSAT to provide is an external watchdog circuit that includes power recycle in the event of a heartbeat not being present from the LPFE or in the event that a watchdog timer is not reset periodically by a ground command station. Rincon plans an LPFE hardware rework to implement the items listed in table 2.

In the software arena, there are several things that could be done to improve radiation tolerance. Experience of other designers suggests that the cache on the microprocessors is subject to single event upsets and should be disabled. They also suggest using the Xilinx secure image function to detect whether a bit image is correct. Multiple "gold copies" of the bootable image would be stored, and sequenced through until a correct image was found.

It is also suggested that the a configuration memory scrubber could be used to detect and repair single event upsets in the main FPGA configuration memory.

Finally, it is suggested that Linux kernel panics and other error messages should trigger certain reboot actions including possibly a power reset.

A major conceptual change for space use of the LPFE is routing all of the command, control, and data via RF links rather than the Ethernet or other wired interfaces as is normally done in terrestrial scenarios.

Finally, AMSAT is planning to implement spacecraft control functions in the LPFE's ARM processors. This has a number of advantages, but it does complicate development and testing of software as two disparate functions share the operating system and compute resources of the ARMs.

Fault tolerance is very important. We note that many of the fault tolerant schemes have a significant software component, so they are subject to software design choices, programmer availability, and schedule limitations. We have already talked about some of these, but we felt it important to re-emphasize them.
.

- External watchdog to monitor LPFE heartbeat and keep alive timer and reset if necessary
- RSA-authenticated bootstrap from NAND flash with multiple "golden" copies
- ECC memory controller for DDR3 within Zynq
- Internal watchdogs within Zynq
- Potential FPGA configuration scrubber
- Redundant processing streams with "voting"

Table 3: Some (largely software) items that could improve fault tolerance. Our ability to implement some of these may be limited by the schedule and the size of the programming team.

Items not yet mentioned include the possibility of repeat "scrubbing" of the FPGA bit mask to discover and correct for any single-event-upsets in the FPGA fabric. This is an item unique to FPGAs and may not be familiar to programmers. Another new item, redundant processing streams with "voting" is well-known in concept, but of course there are details that can achieve most of the beneficial effects of voting while using less compute resources.

6. Summary

Rincon Research is very excited by the prospect of incorporating Rincon Hardware into an AMSAT payload. We do this in part to pay back all the people and organizations that have helped us over the years. We also do it because many of us are hams and it is a cool project.

Time is extremely short. This project would be impossible if we were not starting with an existing design that allows us to begin software development immediately. It would also be impossible to have a payload ready for integration in less than a year if we didn't adopt the approach of having a minimal set of spacecraft code ready at spacecraft integration and loading additional code on orbit.

In this paper we have outlined a success-oriented plan for the LPFE part of the payload. As this is being written in early September 2015 we have no visibility into progress on the rest of the payload or how this will all come together.

Rincon Research has a sense of urgency in two areas:

1) Completing a rework of the LPFE board optimized for space
2) Giving AMSAT developers access to LPFEs for software development and testing

Rincon views spacecraft software development as a significant schedule risk, and Rincon has put a spacecraft software development facility on the internet for use by AMSAT developers.

The authors and Rincon Research: All authors are employees of Rincon Research Corporation headquartered in Tucson, AZ. Rincon is a company of about 200 employees mainly supporting the US government. It also has offices in Colorado and Virginia, and employees are scattered around the globe. Rincon sponsored and provided technical support for RinconSat, an early CubeSat built by the University of Arizona. Unfortunately its Russian launch vehicle failed.

Fox-1E - Proposed IHU Firmware Features

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A 5th Fox series satellite ,designated Fox-1E, has been proposed. This satellite will differ from the earlier member of the series (Fox-1A, Fox-1B, Fox-1Cliff, and Fox-1D) in several important respects. A linear transponder will replace the earlier satellites' single-channel FM bent pipes. The telemetry down-link will be consolidate the low-speed (200bps) and high-speed (9600 bps) modes used by the earlier machines [1] with one 1200 bps binary phase-shift keying (BPSK) [2] telemetry down-link signal. In addition, Whole Orbit Data (WOD) and Slow Scan Television (SSTV) have been proposed as features that might be included in Fox-1E.

This paper summarizes the IHU firmware changes necessary to implement these features. A testing configuration is described that will provide the ability to test the new IHU features prior to building engineering model hardware.

Whole Orbit Data

The WOD function will collect the following parameters at one second intervals:

- battery voltage
- solar panel output voltage
- IHU temperature
- PSU temperature
- battery board temperature

The WOD feature's storage requirement is modest. Since each parameter requires 12 bits of storage, a complete WOD sample will require 60 bits of storage. One solar day of WOD can be stored in 10.5 KB of storage. Table 1 below summarizes the BPSK down-link's performance with respect to WOD payload size. The telemetry frames transmitted by the satellite are inflated in size by the application of a Reed-Solomon FEC code and 10b8b encoding. This formula was used used to calculate the fully burdened frame length in bits:

frame length = 10 · (packet length + ceiling(packet length/233) ·32). Note: the packet length unit used in this formula is 8-bit bytes.

Several issues need to be resolved before the WOD packet format can be designed and the WOD

feature is added to the IHU's firmware:

How much WOD data do we want to store in the satellite? The answer to this question will depend upon the orbit period, on the amount of data that we downlink to support science experiment payload(s) installed in the satellite, and on the method used to share the BPSK down-link's throughput.

Do we want to retain the current time division multiplexing scheme for all downlinked telemetry or do we need to shift to ground commanded downlinks of WOD or science telemetry? A simple time division multiplexing scheme is used in the current Fox satellites to share downlink throughput. Table 2 lists the downlink times for the packet formats used in the current Fox satellites when downlinked on Fox-1E's 1200 bps BPSK signal. Using the information in tables 1 and 2, combined with accurate science payload dowlink requirements we will have the information necessary to make this decision.

WOD Period (Hours)	Packet Length (bytes)	Frame Length (bits)	Downlink Time (seconds)
1 ½	675	7710	6.4
6	2700	30,520	25.4
12	5400	61,360	51.1
24	10800	122,720	102.3

Table 1 – WOD Down-link Time (1200 bps BPSK).

Payload Type	Packet Length (bytes)	Frame Length (bits)	Downlink Time (seconds)
Type-1 Real-Time	66	1000	0.83
Type-2 Maximum Values	66	1000	0.83
Type-3 Minimum Values	66	1000	0.83
Type-4 Radiation Experiment	64	960	0.80

Table 2 – Fox-1 Telemetry Payload Down-link Times (1200 bps BPSK).

Generating BPSK via Software

Figure 1 shows the flow of data between hardware components when the BPSK downlink is synthesized by a software process. For the purposes of this discussion we are going to assume that the BPSK signal's bit rate (baud rate) and the carrier frequency are both 1200 Hz. This scheme can easily be adapted to different baud rates and carrier frequencies.

One hardware timer is used to control the process by pacing the flow of sin() function values stored in a lookup table into an ADC built into the IHU's microcontroller. This data transfer is performed by a DMA channel, built in to the microcontroller, in response to request pulses received from the timer. Each time a complete bit cell is outputted by the DAC the DMA channel will generate an interrupt signal.

The ARM Cortex-M3 CPU [4] included in the STM32L microcontroller [5] provides feature called bit-banding. Bit-banding is another name for bit addressing. This CPU feature provides alias bit addresses for all locations in the microcontroller's SRAM memory. Thus allowing ARM software to access individual bits in SRAM with out incurring the the overhead of masking shifting operations that would otherwise be necessary.

Figure 2 illustrates the major activities performed by the software when generating BPSK. The flow-chart on the left side shows the activities that occur in the IHU's *Audio* FreeRTOS task. Three variables are used in *Audio.* Variable *bit_ptr* is a bit-banding address (bit address) that points at the BPSK message buffer, *length* is the length of the message in bits, and a FreeRTOS binary semaphore [6]. When a BPSK frame is ready for transmission *bit_ptr,* and *length* are set to the appropriate values and the DMA channel is given the start command. The *Audio* task then waits on the binary semaphore using the FreeRTOS *xSemaphoreTake()* function.

The flow-chart on the right side of Figure 2 shows how the DMA channel's interrupt service routine functions. The first activity performed is to check the *length* variable's value, if it is zero the BPSK message is complete, the *Audio* task is released from its wait state with by signaling using the FreeRTOS *xSemaphoreGiveFromISR()* function. If *length* is a non-zero value, the ISR examines the next message bit, adjusts carrier phase as necessary, decrements *length*, and starts the next bit cell's transmission by issuing a DMA start command.

The DMA interrupt service routine consumes less than 1% of available CPU time (the ARM CPU clock = 32 MHz). The ARM CPU requires 24 cycles to enter and exit an interrupt service routine (12 cycles on entry, 12 cycles at the exit). If assume 100 cycles of processor time are used in the interrupt service routine (likely an over estimate) each interrupt will consume 124 clock cycles. The burden on the CPU will be $(124 \cdot 1200 / 32 \cdot 10^6) \cdot 100\% = 0.47\ \%$.

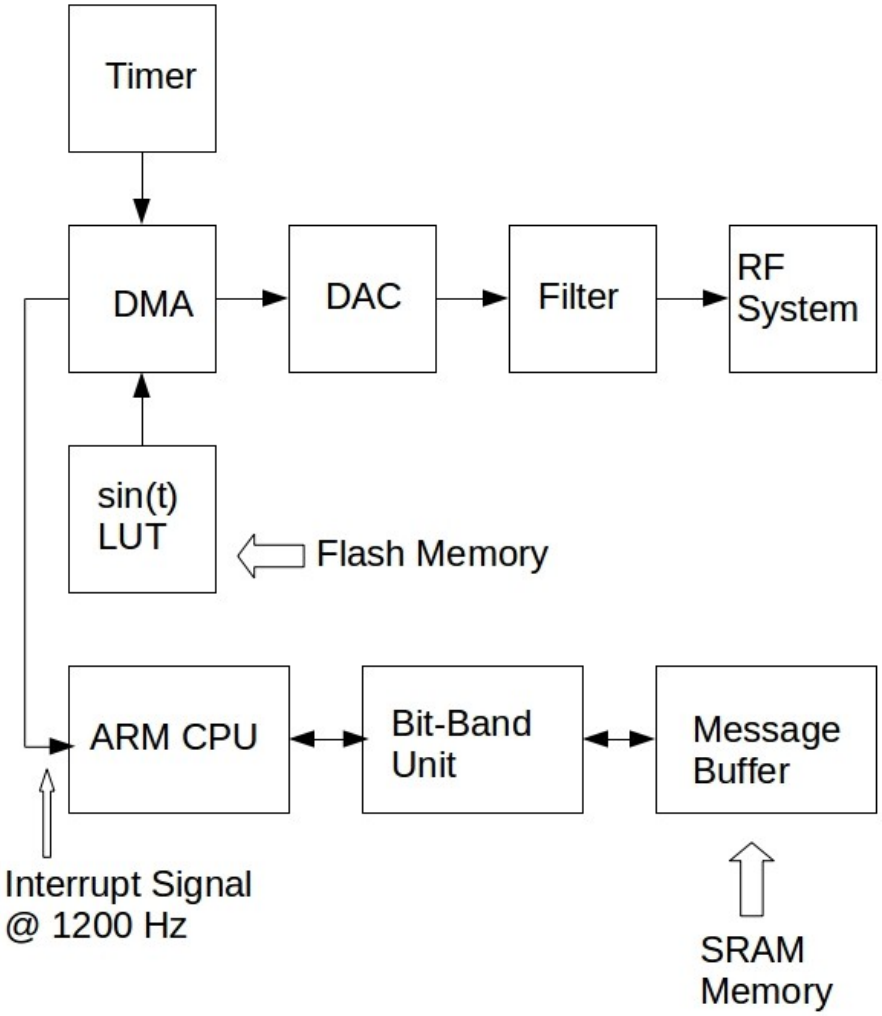

Figure 1 – Generating BPSK via Software.

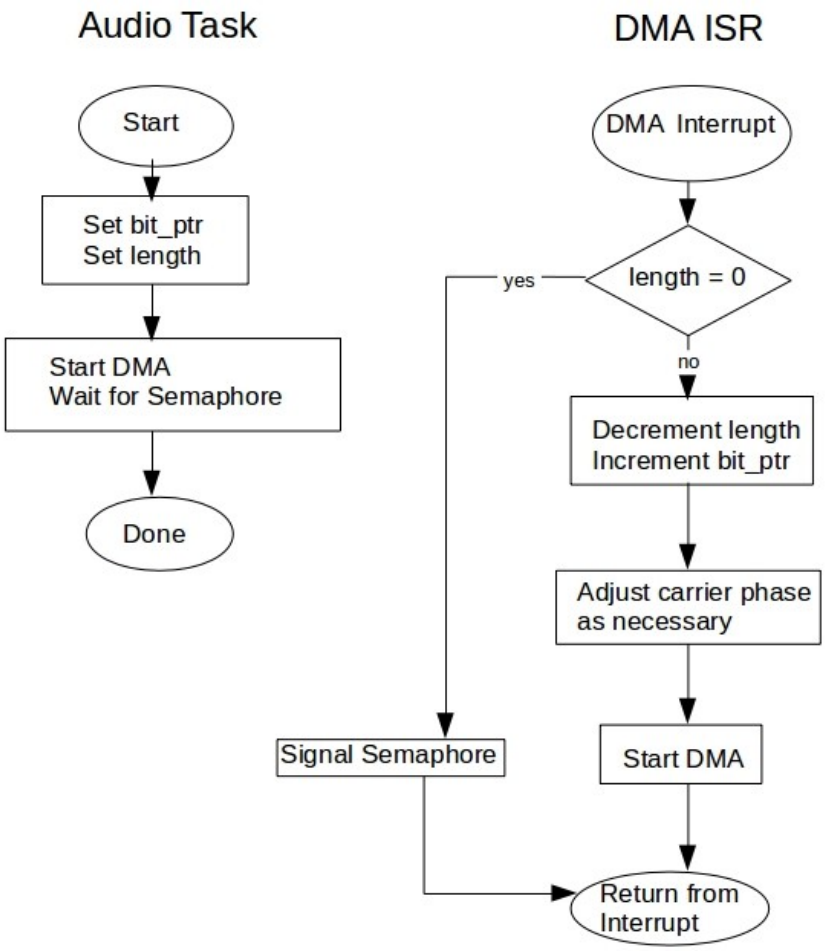

Figure 2 – BPSK Software Components.

Generating SSTV Signals

Figure 3 provides a overview of the interaction of hardware and software components when generating a SSTV signal. Two hardware timers are needed, one timer is used to control the sampling rate used when generating the sinusoidal signal, providing a way to control the audio signal's frequency. The other timer is used to control the duration of each SSTV tone transmitted. The tone duration timer acts as an interrupt input to the ARM CPU, reception of this interrupt signal tells the software that an SSTV picture component's transmission has been completed. The sample interval timer acts as DMA request signal causing the DMA channel to read a value from the sin() function lookup table and pass its value to the microcontroller's ADC.

Figure 4 shows the software activities required to transmit a SSTV signal. The left side of Figure 4 is a flow-chart of the actions that occur in the IHU's *Experiment* task. The *Experiment* task determines which sequence of audio tones are needed to generate the desired image and commands the DMA controller to transmit those tones. The *Experiment* task commands the transmission of a SSTV picture element by selecting an audio frequency (setting the sampling interval timer's value), configuring the tone interval timer to fire when the tone's transmission has been completed, and issuing a DMA start command to begin the transmission of the tone. The *Telemetry* task then waits on FreeRTOS semaphore.

The right had side of Figure 4 is the interrupt service routine that is called when the tone duration timer expires. The interrupt service routine executes a signal operation on the semaphore, taking the *Experiment* task out of the wait state , and issuing a DMA stop command causing the tone output to cease.

The the 8s (60Hz) SSTV mode [7] [8] is useful under difficult signal conditions. We can use this SSTV mode to estimate the CPU load created when transmitting a black and white SSTV image. Each 8s mode scan line is 55ms in duration, the horizontal resolution 128 pixels per scan line. The time interval between pixels will be 55 ms / 128 or 0.43 ms. This means that a pixels are sent 2326 times per second. If we assume that the interrupt service routine requires 124 cycles to execute. The CPU load imposed by the interval timer interrupt service routine will be $((2326 \cdot 124) / 32 \cdot 10^6) \cdot 100\% = 0.90\ \%$.

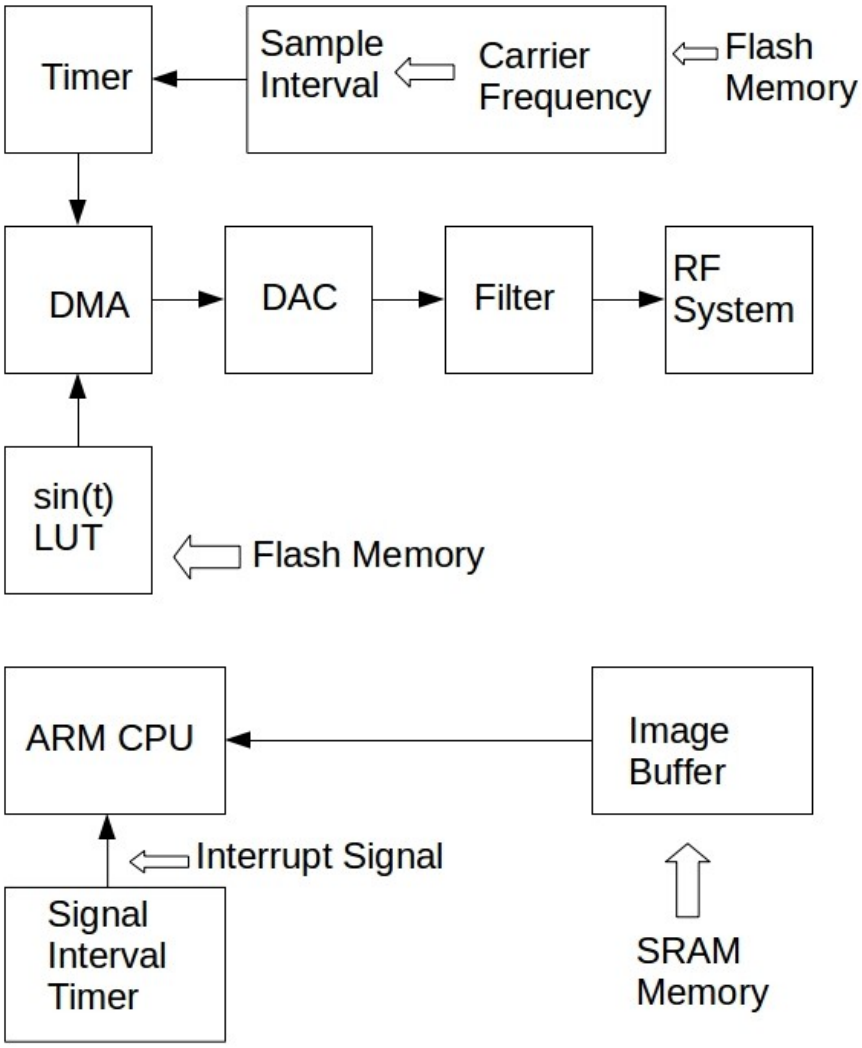

Figure 3 – Generating SSTV Signals.

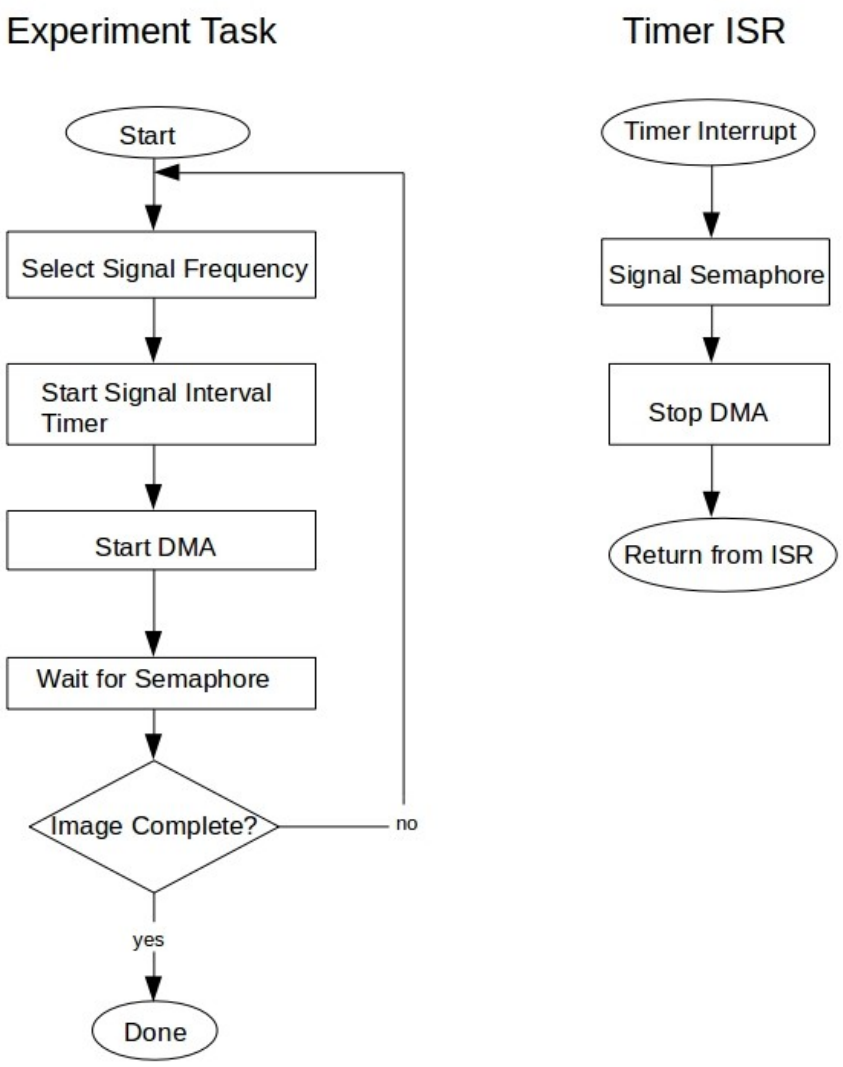

Figure 4 – SSTV Software Components.

Testing Fox-1E's Firmware

Figure 5 below shows a testing scheme that can be used to test BPSK telemetry and SSTV transmission. This scheme does not provide a complete simulation of the satellite, instead it provides the firmware developer a working model that can generate SSTV or telemetry signals outputted as as baseband audio or as a RF signal.

The IHU Simulator [13] contains a ST Microelectronics micro-controller [5] that is functionally identical to the MCU used in the satellite. Both the satellite and the IHU simulator use 32 MHz CPU clocks.

The baseband audio signal output by the IHU Simulator will contain significant high frequency components that must be eliminated. An active audio filter [12], configured as a low-pass filter, built on a solder-less breadboard or perf board, will be used to eliminate the unwanted high-frequency components. The filtered baseband audio output can be fed directly into the microphone input of a computer for processing. Alternatively, the baseband audio can be used to generate a RF signal for testing.

A balanced modulator circuit, using one of the commonly available balanced modulator integrated circuits (MC1496 [10] or AD630 [9]), assembled dead bug style on PCB stock, will be constructed. The balanced modulator's carrier input will be driven by a RF signal generator, the RF signal generator frequency setting establishes the (suppressed) carrier frequency of the DSB signal outputted by the balanced modulator. The operating frequency will be an unoccupied frequency on the AM broadcast band (510 kHz – 1705 kHz) [11]. The DSB signal will be filtered with a low-pass filter before being passed to the antenna.

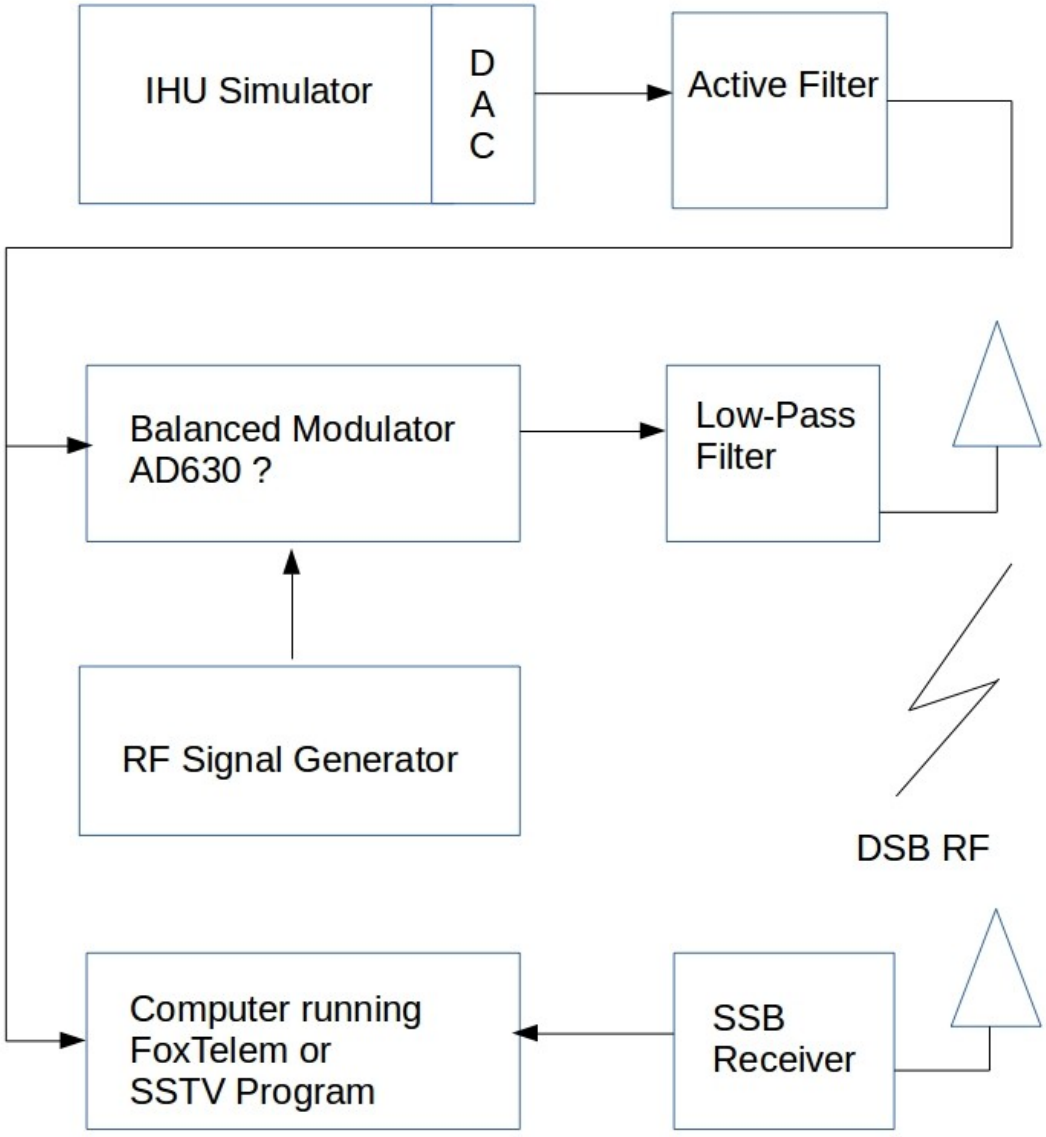

Figure 5 – Testing Fox-1E's Firmware.

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A Modern Approach To Secure Commanding of an Amateur Satellite

By Burns Fisher, W2BFJ – V1.4, Sep 23, 2015

All US ham radio satellites are required by the FCC to have the capability of being made to stop transmitting by telecommand[1]. Other countries have similar restrictions. Thus every OSCAR must have at least some uplink command capability. In practice, most amateur satellites are designed to accept a number of commands for different purposes. One concern that a satellite designer must take into account is the possibility that such a command would be sent by unauthorized ground stations. Commonly, this concern has been addressed by keeping the commanding protocol or the command frequency secret. This paper proposes a more modern approach to solving the problem of secure satellite commanding.

I don't intend this paper to go into mathematical detail about the techniques I will discuss. Details are easily found, and I will give references along with analogies (which you should verify against the math for yourself if you wish). The goal is that if you convince yourself of the math, the paper will convince you that it can be applied to satellite commanding.

Security by Obscurity

In the security community, preventing unauthorized access by not publishing the command protocol or frequency would be called an example of "security by obscurity"[2]. This moniker generally implies that there is no theoretical barrier to someone breaking the security. Keeping the details secret only makes breaking it slightly harder.

In addition, obscurity requires that some of the satellite design be hidden not only from the public, but also from volunteers building the satellite. This is philosophically troublesome when we consider AMSAT's general philosophy of open publication of everything, and tactically troublesome when we wish to put, say, a schematic or software that includes a command decoder in a repository available to all volunteers.

An obvious technique to improve commanding security would be to encrypt the commands. The security community considers an encryption technique robust only if the details of the algorithm are openly published so that experts can scrutinize them for flaws (even by experts whose motivation is their wish to break the encryption). This matches well with AMSAT's open publication philosophy.

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[1] Title 47 US Code Regulations Part 97.207(b)

[2] http://en.wikipedia.org/wiki/Security_through_obscurity

Regulatory Aspects of Encryption

Before we go further, let me address the regulatory aspects of encryption by hams. Hams are prohibited from transmitting "messages encoded for the purpose of obscuring their meaning, except as otherwise provided herein[3]". And one of the exceptions listed is that the telecommand station for a ham satellite "may transmit special codes intended to obscure the meaning of telecommand messages to the station in space operation."[4] In other words, it is perfectly legal (in the United States at least) to transmit encrypted commands to a ham radio satellite.

As we shall see, however, we don't necessarily need to play lawyer with the regulations and assume that fully encrypted commands are acceptable, not do we have to worry about regulations from other states. We merely need to arrange the command messages so that only a legitimate ground station can send valid command messages, even though anyone can read them. Or put another way, the satellite must be able to *authenticate* that the message came from a legitimate ground station.

I will describe two techniques which, combined, are called *Digital Signing* [5], a technique which can allow a recipient to verify that a set of data was created by a known party. Then I will show how these techniques can be applied to satellite commanding.

Public Key or Asymmetric Cryptography

Many cryptographic algorithms rely on both sender and recipient knowing a secret key (symmetric cryptography). For example, suppose the algorithm is "Encrypt a letter by adding the secret key to it modulo 26". If the secret key is '10' then the plaintext ZOO is encrypted as JYY. To decrypt, you subtract the same secret key from the encrypted text in the same way. This example is obviously a very poor algorithm, but it does serve to show that with symmetric cryptography, both sender and recipient need a copy of the secret key, and that this one key must be kept secret from anyone who is to be prevented from reading the message or creating a new message.

Asymmetric cryptography, on the other hand, uses a pair of keys—called a public key and a private key--one to encrypt and one to decrypt. In addition, the keys are reversible (i.e. you can encrypt with either key as long as you decrypt with the opposite key). Clearly the keys must be mathematically related. Another required property is that it is impossible (really computationally infeasible with current hardware) to derive the private key from the public key. As you can guess from their names, its "owner" keeps the private key secret. The public key can be freely distributed without any secrecy.

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[3] IBID, 97.113 (4)
[4] IBID, 97.211(b)
[5] http://en.wikipedia.org/wiki/Digital_signature

I will not describe the math behind public key algorithms,[6] but I will give you a feasibility example for a public and private key. Suppose that the private key is a pair of very large prime numbers. The public key is the product of these two prime numbers. Or put another way, the private key consists of the prime factors of the public key. It is relative easy to generate prime numbers, and thus to generate a private key. It is relatively easy to multiply two prime numbers and thus to produce the private key. It is VERY difficult to calculate the prime factors of the public key.

As an example of how this technique can be used, imagine two people named Allen and Betty who want to communicate securely. A third person, Carolyn, can intercept the message sent between them. Allen has his own private key as well as Betty's public key. Betty has her private key and Allen's public key. Carolyn has both public keys. Allen wants to send Betty a secret message. He encrypts the message with BETTY's public key. Now only Betty can decrypt the message because only she has her private key. Carolyn cannot read the message.
Suppose now that Allen instead wants to send Betty a message which is not secret but which she must be able to authenticate as coming from him. Allen encrypts the message with his own secret key. Now anyone, including Carolyn and Betty, can decrypt the message with Allen's public key, but if it decrypts, Betty or Carolyn will know Allen encrypted it because only Allen has the private key.
Similarly, Betty could send Allen a message encrypted with BOTH Betty's private key and Allen's public key. Now only Allen can decrypt it, and he can also be confident that Betty was the one who encrypted it. Carolyn might decrypt the message to one level using Betty's public key. She will then know it came from Betty, but she can't read the message without Allen's private key.

Message Digest or Secure Hash

Consider the "checksum", a rather old but familiar way to validate the contents of a message. To generate a simple checksum, you just add each byte of the message modulo 256. You then transmit the checksum along with the message. If the receiver does the same calculation she should come up with the same resulting checksum. The checksum could be called a message digest. Of course it is very easy to come up with several messages that have the same checksum, so this is a very poor digest and a poor technique for validating a message.

Modern message digests are generated using one of a number of algorithms called "Secure Hashes". These secure hashes have several important cryptographic characteristics[7]:

- it is easy to compute the hash value for any given message
- it is infeasible to generate a message from its hash
- it is infeasible to modify a message without changing the hash
- it is infeasible to find two different messages with the same hash.

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[6] http://nrich.maths.org/2200 for example
[7] http://en.wikipedia.org/wiki/Cryptographic_hash_function

In addition, we wish a small change in the message to make a large change in the digest. An example of such a secure hash is the family of algorithms known as SHA-2[8] (of which SHA225 shown in the example below is a member)

> Even a small change in the message will (with overwhelming probability) result in a mostly different hash, due to the avalanche effect. For example, adding a period to the end of the sentence:
> `SHA224("The quick brown fox jumps over the lazy dog")`
> `0x730e109bd7a8a32b1cb9d9a09aa2325d2430587ddbc0c38bad911525`
> `SHA224("The quick brown fox jumps over the lazy dog.")`
> `0x619cba8e8e05826e9b8c519c0a5c68f4fb653e8a3d8aa04bb2c8cd4c`[9]

Digital Signature

We can now combine these techniques into what is known as a digital signature. First we generate a digest of the message. Then we encrypt the digest with the private key of the sender. Our hypothetical person Betty can now be certain that the long message she got from Allen was indeed written by Allen. All she needs to do is to generate a message digest from the message, and then decrypt the encrypted digest using Allen's public key. If they match, she can be sure that she received exactly what Allen sent, and also that Allen himself sent it.

This is the technique that is currently used to distribute software on the Internet. If you update Windows, your iPhone, or most other software, you will notice that there is brief message that says something like "authenticating". This is the time when the software on your computer is generating the digest and decrypting the digital signature.

Application to Satellite Commanding

One issue about encryption and digital signing is that it typically requires a computer on both the sending and receiving end. Some satellites, such as the Fox-1 family, have been designed so that the IHU (internal housekeeping unit, or computer) is not mission-critical on the assumption that radiation may kill the IHU before it kills the transponder hardware. However, in future satellites that plan to use software defined radios, the IHU is designed to be mission critical anyway, so we might as well use it for another critical function such as authenticating an uplinked command.

Here is a way to use Digital Signing for satellite command encryption: Before launch the command station generates a public/private key pair and sends (open email is ok) the public key to the software developers to incorporate into the satellite

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[8] http://en.wikipedia.org/wiki/SHA-2
[9] IBID

software. The command station keeps the private key secret. When the time comes to send a command, the command station sends the command (using a publicly known protocol designed for the satellite) followed by the unencrypted message digest, followed by the digest encrypted with the command station private key. The satellite validates the message using Betty's technique in the "Digital Signature" section. If it validates, then the satellite acts on the command.

Why do we send the unencrypted message digest? It is not really necessary, but it avoids arguing about governmental rules and encryption. If we send the unencrypted digest, then there is nothing at all in the message that is obscured because the signature is known to mean exactly the same thing as the digest.

One remaining problem: For software updates, we don't care whether someone intercepted and retransmitted the code. As long as the recipient knows that (for example) Microsoft or Apple generated the code in the first place, it is not important where it spent time in the middle. (In fact travelling the Internet, the software update no doubt spends a lot of time on unknown machines and disk drives.) The issue is different for satellite commanding. We don't want an unknown person to intercept a commanding session and replay it to the satellite at the wrong time.

My solution to this problem assumes that the satellite beacon includes a timestamp of some sort. For example, the Fox-1 satellites send "number of reboots" and "seconds since last reboot" as a pair forming a unique timestamp with each data packet. Any sequence would work, however, including simply an incrementing sequence number sent with each downlink packet.

The ground station must hear the beacon within a certain time interval (Ti) before sending a command, and then include a satellite-originated timestamp in the command. The satellite, as part of the authentication calculation, compares the received timestamp to ensure both that it is newer than (current time – Ti), and newer than the most recent successfully authenticated command.

Now if a "bad guy" intercepts a command to the satellite and resends it, it will fail authentication if any of the following happen

1) The satellite received the original authentic command or the satellite received an authentic command since the duplicate command was originally transmitted (in which case the fake command will fail the "since the timestamp of the most recently authenticated command" test)
2) The "bad guy" waits a while to send his fake command (in which case the fake command will fail the "timestamp within Ti" test)

The bad guy might resend a command which authentic ground station just sent, but which the satellite did not receive successfully. In this case the bad guy is helping us since the ground station presumably wanted the satellite to receive his command anyway.

A Few Additional Thoughts

Muliple Controllers*:* Suppose that you wanted different ground controllers to have the ability to send different subsets of commands. In this case, each ground controller would generate her own key pair. The satellite would know all public keys of all ground controllers, and which commands each one was allowed to send. Then we would add another rule saying that the command must be authenticated using the public key of a ground command station that is authorized to send the command.

Authenticating Downlink: One could also use this same technique to authenticate a downlink by have the satellite 'sign' its transmissions with its own private key. This could be useful to separate ground test transmissions from on-orbit tests, or simply to prevent black-hats from filling the ground repository with fake downlinks.

Why a digest? You might ask why we need to make a digest if the command is small. There are two reasons:

1. We want to guarantee a big change in the value that is being encrypted to form the signature even if there is only a small change in the plaintext. For example we might send the same command several times, but you would like the signature to be significantly different even if they only differ by a few seconds in the time stamp.
2. You might wish to use this technique just as computer companies use it now: To ensure the integrity of software uploads to the satellite. In this case, the software will be considerably larger, and a digest makes the entire process more practical.

What's wrong with secrecy? You might ask why I am so insistent on non-secrecy. While I believe in sharing as much info as possible, I have nothing against some sensitive information being hidden; I would even recommend that things like the command protocol not be published. However, secrets WILL be revealed over time, intentionally or not. It is best to design assuming that nearly everything will be public, and then hide some data as an extra layer of protection.

Summary

Simply keeping the codes, protocols, and frequencies for satellite commanding secret is not only insecure, but it is philosophically troublesome for AMSAT's open method of operating and tactically troublesome to keep parts of the design hidden from our volunteers. As more sophisticated satellites have more requirements for mission-critical computers, we have computation power available to use modern encryption techniques that allow for secure satellite commanding.

This paper proposes using now-standard Digital Signature techniques, with a small variation that avoids resend attacks, to command amateur satellites. Using this technique, all hardware and software can be completely open and public without compromising the security of commanding the satellite. This paper also shows that

while FCC Part 97 allows encrypted commanding of a satellite from the US, it is possible to use digital signing to send a secure command without any obfuscation of any part of the uplinked command.

Thanks

Thanks to Brian McCarthy, N1ZZD for reviewing this paper and to Mike Zaharee KE1EB for suggesting some additional reading.

Ragnarok Industries CubeQuest Challenge Mission

AMSAT has partnered with Ragnarok Industries on a lunar satellite mission. AMSAT is providing the primary radio communications system while Ragnarok designs and integrates the other subsystems of the satellite design. Upon completion of the primary mission, the satellite will remain in lunar orbit (10,000 km radius) providing voice relay for any amateur user via AMSAT's ASCENT radio transponder. The operating frequencies are in the amateur bands near 5.67 GHz for uplink and 10.5 GHz downlink. The launch is currently scheduled for 2018.

Ragnarok Industries formed in 2014 in order to participate in NASA's CubeQuest Challenge, a competition funded by NASA's Centennial Challenges program. After a two year development period, the top three satellites from the competition will be awarded a spot on the first flight of the Space Launch System, NASA's new rocket which is preparing to deliver the manned Orion crew module to Mars in the 2030s or later. Through a series of four design reviews, known as Ground Tournaments (GT), NASA will select the top 5 highest scoring teams (June 2015, Jan 2016, June 2016, Jan 2017). We are pleased to announce that Ragnarok was selected as one of the winners of GT1 in early September. Such a victory would not have been possible without AMSAT's support.

Known as the Norse mythological figure who blows his horn to signal the start of Ragnarok, the satellite "Heimdallr" will be a 6U (1U = 10 cm^3) shoebox-sized satellite that features 3-axis stabilization, 4 reaction wheels, nearly 100 Watts of Solar Power Generation, cold gas propulsion, and RF Ion Propulsion to complete this Lunar Mission. A new radiation-tolerant guidance, navigation, and control system will be developed in-house. Heimdallr will be carry a digital regenerative transponder designed by the AMSAT Ascent team.

Although the satellite will support amateur use through voice relay, AMSAT members can also become involved in the mission itself. AMSAT users with a minimum size of 1-meter X-band receivers will be able to capture precious telemetry needed to determine spacecraft position and velocity before critical maneuvers, as part of Orbit Determination. This particular method of Orbit Determination involving dozens of Amateur Radio Operators has never been performed before. Downloaded telemetry will be uploaded to a server through the internet.

Analysis of elliptical orbit perturbations with NASA's General Mission Analysis Tool

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I have previously reported (**1**) on an effort to reproduce the observed orbital behavior of the AMSAT-OSCAR-13 satellite using an earlier version of NASA's General Mission Analysis Tool (GMAT). This paper is a brief progress report on efforts to fully understand the forces acting on a satellite in elliptical orbit and to develop a strategy to use low thrust propulsion to control the orbital evolution of that satellite.

Orbital analysis will be an important part of any AMSAT proposal for future HEO satellite launches. Satellite Tool Kit (**2**) is a widely recognized industry standard software package for that purpose. Many universities have academic licenses for STK but as far as I know AMSAT does not have access to this tool. GMAT provides a free open source alternative that will enable AMSAT to perform the necessary flight dynamics analysis to support our proposals and our eventual mission planning needs.

NASA Goddard Space Flight Center spends about $800,000 per year (**3**) on software licenses for Satellite Tool Kit and other software tools, and still does not have access to the internal workings of that program. For this reason, NASA has been developing the open source General Mission Analysis Tool (**4**). Since my previous paper on GMAT, newer versions have been released so that GMAT is even more capable than it was in 2012. GMAT has been used for the analysis of several NASA missions including LCROSS, ARTEMIS, LRO, MMS, and OSIRIS (**3**) and the NASA sponsored Lunar IceCube 6U Cubesat mission that will be launched on the first flight of the Space Launch System (EM-1)..

Like many open source projects, the documentation tends to lag behind the development, which presents a challenge to neophytes attempting to learn the operation of the program. There are many opportunities for those who wish to contribute effort toward further development, testing and documentation. GMAT contains a graphical user interface that sets up many of the program inputs, but since I learned programming back in the days when we submitted decks of punched paper cards through a window at the computer center, I felt more comfortable writing the input script directly.

Sensitivity to initial Right Ascension of Ascending Node (RAAN)

The original work in modeling OSCAR-13 as reported in the 2012 paper was repeated in order to validate the results with the newer version of GMAT. I then varied the RAAN in 30 degree increments while keeping all other elements the same. Initial RAAN values from 237 degrees through 307 degrees caused the perigee height to dip into the atmosphere within seven to nine years after launch. RAAN values outside of this range remained in orbit for at least 15,000 orbits, or almost 20 years. OSCAR-13 had the misfortune of launching with an initial RAAN value of 247 degrees, which placed it in the region of instability. Because the satellite carried no on-board propulsion following depletion of the fuel tanks, its fate was sealed on the day that it was launched.

The RAAN rotates at a rate of about 90 degrees per year, completing a full 360 degree cycle about every four years. I have yet to develop a clear understanding of why the initial value of the RAAN is so important in determining the ultimate fate of the satellite. Now that we have all of this data we have to figure out what it is trying to tell us.

RAAN	Orbits	Run Time (sec)	Run Ended Date	minimum altitude	
007.538	>15000	4817.313	10 Feb 2008+	2153 km on 31 Jan 1991	
037.538	>15000	4536.925	10 Feb 2008+	2297 km on 15 Mar 1991	
067.538	>15000	4689.737	10 Feb 2008+	2495 km on Dec 25 1990	
097.538	>15000	4326.777	10 Feb 2008+	2838 km on 26 Jan 1993	
127.538	>15000	4623.346	10 Feb 2008+	2447 km on 03 Dec 1991	
157.538	>15000	4682.206	10 Feb 2008+	2074 km on 18 May 1992	
187.538	>15000	#10635.021	10 Feb 2008+	1514 kn on 01 Jun 1992	
217.538	>15000	#9062.118	10 Feb 2008+	951 km on 13 Jul 1992	
247.538	6142	8237.089	18 Jul 1996	*300 km on 06 Mar 1996	**<AO-13**
277.538	5577	1877.652	22 Oct 1995	*300 km on 12 Aug 1995	
307.538	7354	4669.384	15 Feb 1998	*300 km on 13 Jun 1997	
337.538	>25000	8313.724	01 Mar 2021++	961 km on 03 Mar 2006	

+10 Feb 2008 represents the date when 15,000 orbits was reached, simulation ended at that point.
++The final case was allowed to run for 25,000 orbits, simulation still running on 01 Mar 2021
**Minimum altitude of 300 km was considered to be the beginning of atmospheric reentry.*
#The 187 and 217 degree runs were performed after extensive additions to the script, resulting in much longer run times,

Table 1. Results of GMAT simulation runs for different starting RAAN values

It is important to note that the orbital energy of the satellite remained constant until the beginning of atmospheric reentry, which is considered to begin when the perigee height reaches 300 kilometers. No energy was lost or gained because of the solar and lunar perturbations.

OSCAR-13 was in a 57 degree inclination orbit, which is the basis for the current analysis. This work will need to be repeated for the likely inclinations of future satellite missions, including the 63 degree Molniya orbit and geosynchronous transfer orbits of around 12 degrees.

Effects of Solar and Lunar perturbations on eccentricity and inclination

The GMAT program contains a function to compute the solar beta angle, which is the angle that the Sun makes with the orbit plane. To compute the equivalent “lunar beta angle” it was necessary to add commands to the script to generate a unit vector pointing in the direction of the Moon and to compute the dot product of this lunar unit vector with the satellite's orbital angular momentum unit vector These quantities were plotted in an effort to determine the relationship between these angles and the evolution of the orbital eccentricity and inclination. GMAT computes the position of the Sun and Moon internally but it is necessary to add an obscure command to the script that in not in the user documentation in order for the user to access this data, and this resulted in a certain amount of delay and frustration in completing this analysis. For validation, the solar beta angle was computed in the same manner and compared to the results of the built in solar beta angle function.

The GMAT script is configured to propagate the orbit of the satellite through a numerical integrator one orbit at a time, stopping at perigee. Each trip through the For-Next loop represents a single orbit. The satellite's position vector at perigee represents the direction of the semi-major axis of the orbit ellipse, and similar dot products are computed with the solar and lunar vectors to obtain the angles between these bodies and the axis of the ellipse.

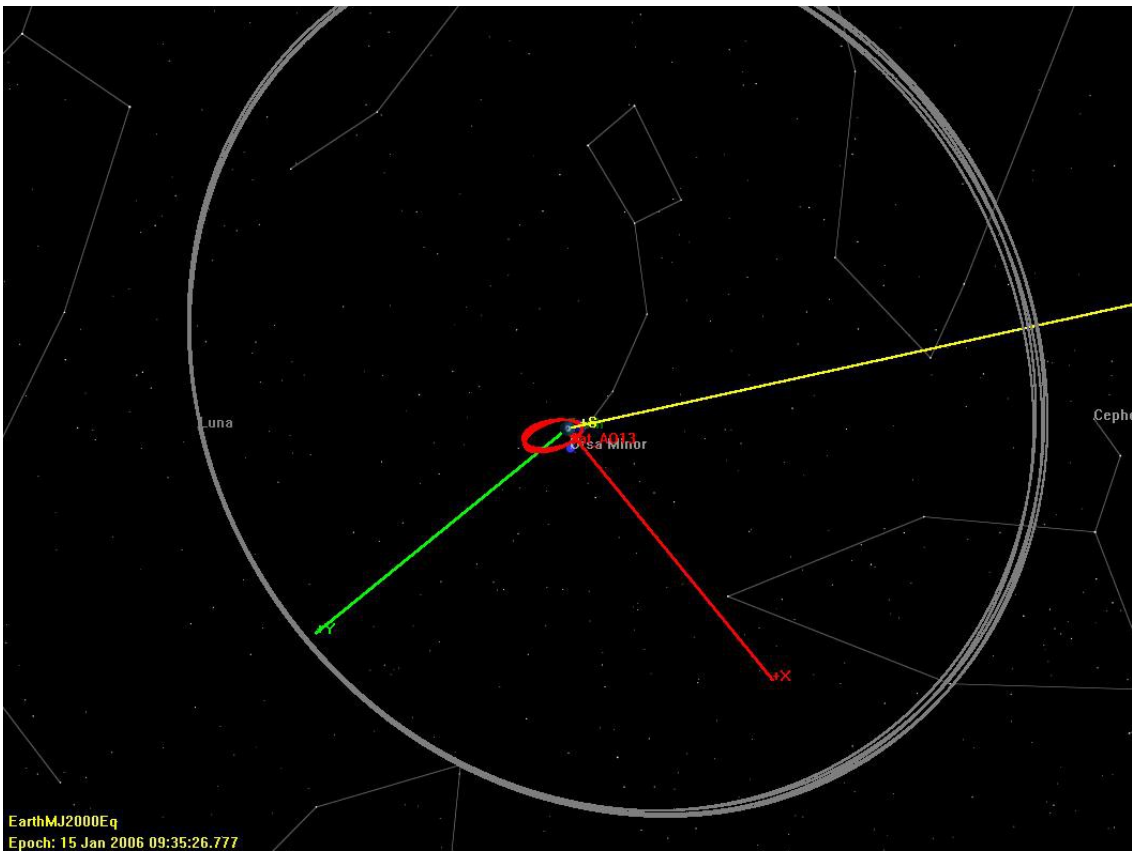

Figure 1. GMAT's orbit view window, looking up from the south pole of Earth. The orbit of the Moon is the large circle (Luna at 9 o'clock), the orbit of AO-13 is the small ellipse in the center. The vector at 2 o'clock points to the Sun. The constellations of the north celestial pole are visible.

The ultimate objective of this exercise is to determine the direction and time of thruster firings needed to control the evolution of the satellite orbit. The goal is to set up an orbit that will provide a long and useful mission to the users and then to reenter on a specific date approximately 25 years after launch to satisfy orbital debris concerns, regardless of the initial value of the RAAN.

My thanks to Joel Parker and Steven Hughes of Goddard Space Flight Center for their help and advice in understanding the operation of GMAT.

References:

(1) Simulation of Historical and Future AMSAT Missions using NASA's Open Source General Mission Analysis Tool, Proceedings of the 2012 AMSAT Space Symposium and Annual Meeting, Orlando, FL
http://www.qsl.net/n8fgv/2012-AMSAT-paper.pdf

(2) http://www.agi.com/products/stk/

(3) NASA GMAT: Space Mission Design for Everyone, Joel J. K. Parker, NASA GSFC
http://cdn.oreillystatic.com/en/assets/1/event/61/The%20General%20Mission%20Analysis%20Tool_%20Open-Source%20Engineering%20at%20NASA%20Goddard%20Presentation.pdf
page 13

(4) http://gmatcentral.org/ and http://gmat.sourceforge.net/blog/

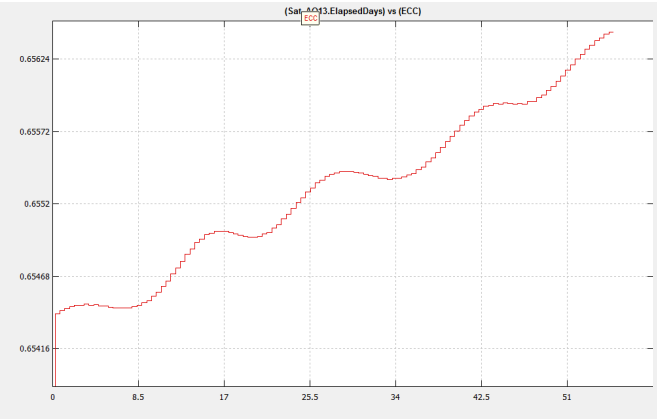

Figure 2. AO-13 Eccentricity.

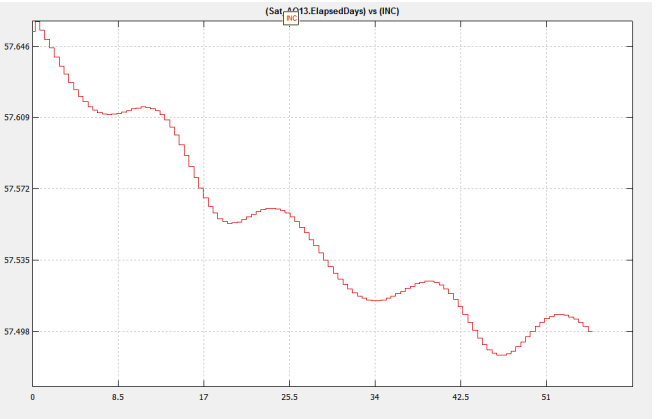

Figure 3. AO-13 Inclination.

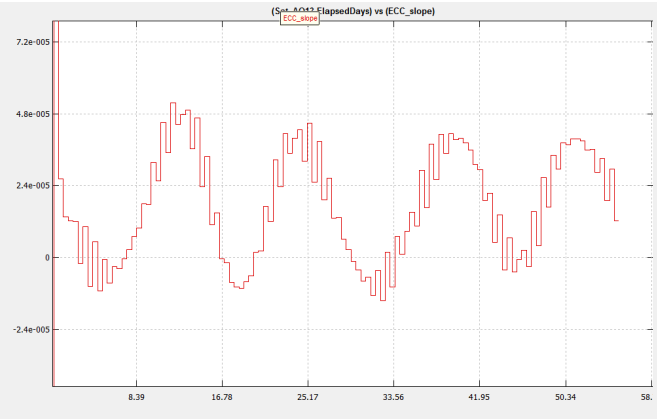

Figure 4. Eccentricity First Derivative.

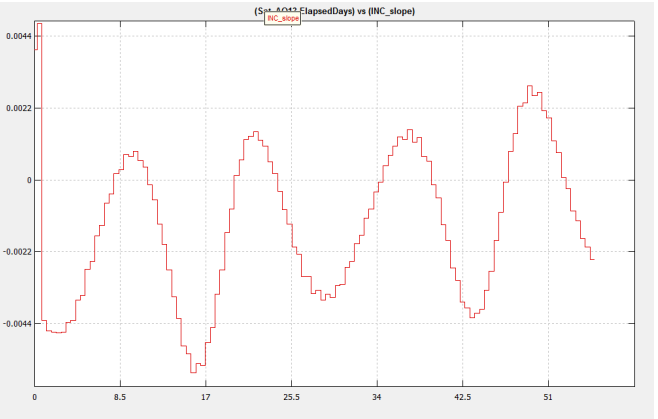

Figure 5. Inclination First Derivative.

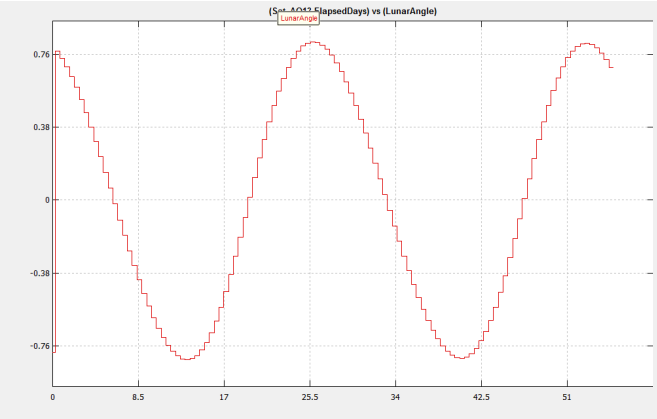

Figure 6. Cosine of angle between Moon and major axis of orbit ellipse.

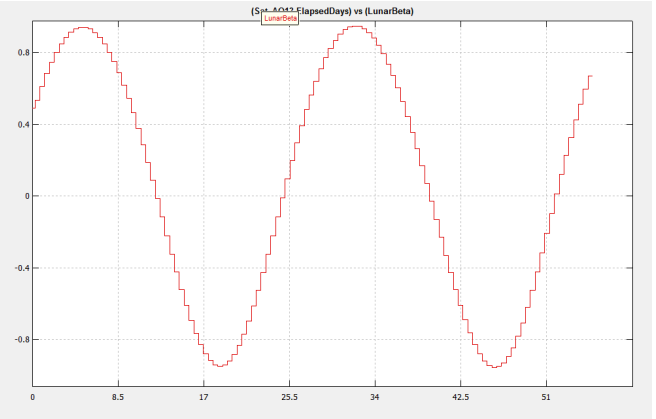

Figure 7. Cosine of "Lunar Beta Angle", angle between Moon and orbit plane.

GMAT plots of OSCAR-13 Eccentricity and Inclination for two lunar orbits. We are looking for relationships between the rate of change in the orbital elements and the Solar and Lunar position vectors.

APRS Satellites, PSK31 and DTMF/Voice

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Dr. Mirek Kasal. OK2AQK, Brno University
Tomáš Urbanec, OK2PNQ

Abstract: PSAT (deployed May 2015) and the coming QIKCOM-2 satellites are offering new capabilities to the AMSAT experimenter that do not require special APRS capable radios. An HF rig and/or any walkie-talkie can be used. In addition to the usual APRS data transponder, PSAT also supports a multi-user PSK31 (10m uplink) text messaging transponder built by students at Brno University in the Czech Republic under the mentorship of Mirek Kasal, OK2AQK. The UHF downlink can be received on any FM radio and displayed on any laptop running any number of free PSK31 clients. The QIKCOM-2 module to fly early 2016, not only contains the APRS data relay but also supports APRS uplink identification and messaging from simpler DTMF radios which gets converted to APRS in the module while also giving Voice feedback to the DTMF user.

Figure 1. PSAT-1 with antennas deployed and QIKCOM-2 module with antennas stowed.

APRS Transponder: The main transponder on both PSAT[1] and QIKCOM-2[2] is a 1200 baud AX.25 Packet Radio Relay similar to what is flying on PCSAT since 2001[3] and the ARISS experiment on the ISS[4]. Both of these missions deliver packets to users worldwide via the global network of volunteer ground stations shown in Figure 2, which also feeds the two downlink capture pages**, http://pcsat.aprs.org** for PCSAT and **http://ariss.net for the ISS**. These pages display live maps of the most recent user position data and capture all message traffic between users.

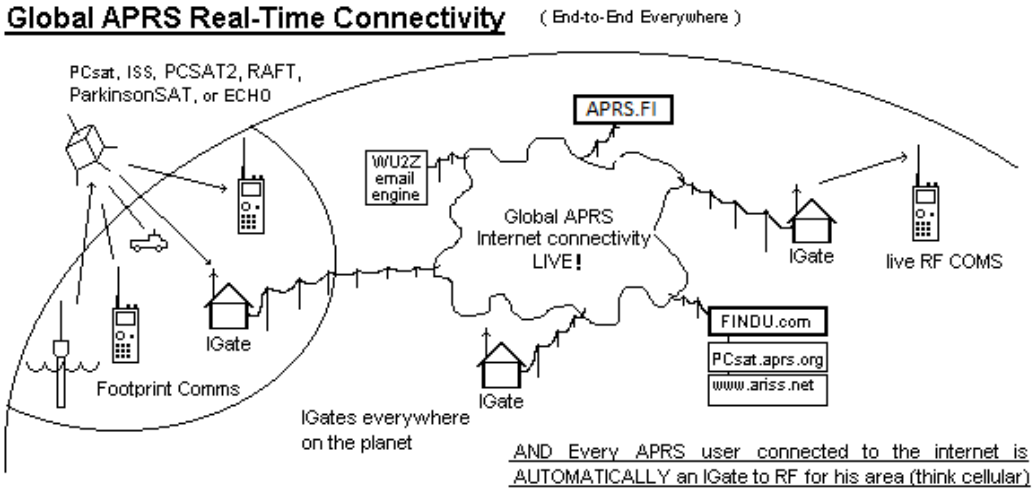

Figure 2. The global APRS network consists of terrestrial as well as internet and satellite links.

Maintaining the Global APRS Satellite Data Channel: We want to maintain as many space digipeaters on the space packet frequency of 145.825 MHz in support of this experimental data channel to provide greater connectivity between users. PSAT pioneers the use of a simple $250 off-the shelf APRS MicroTracker from Byonics.com that fits on one 3.4 inch square card shown in figure 3. Their latest model has a 10W power amp to make a cubesat that can rival the ISS with downlink power.

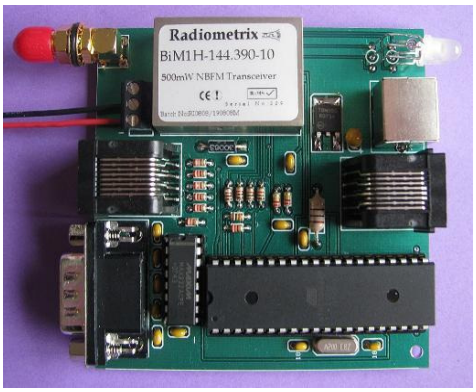

Fig 3. Byonics.com Microtrack-4 Xponder

PSK31 Transponder: The PSK-31 multi-user FDMA transponder[5] experiment built at Brno University is similar to what we flew on RAFT [6] and PCSAT2 [7]. The users on the ground see the full PSK31 waterfall as shown in Figure 4. Since the UHF downlink is FM audio, the 18 kHz Doppler does not affect the individual PSK31 signals but only the FM receiver passband tuning. The users will simply re-tune their FM receivers 5 times during the pass in 5 kHz steps to stay in the passband.

The multiple PSK-31 users transmit using SSB on the 10 meter uplink. There, the Doppler is linear but because it is 14 times lower in frequency than the typical UHF downlink, the total Doppler shift is only about 1 kHz over the pass and typically on the order of about 1 Hz per second during the lower elevation portions of the pass. Most PSK31 software can track this rate. But as the elevation gets higher the rate of Doppler change increases to as much as 6 Hz per second and most clients fail at 2 Hz/s and above.

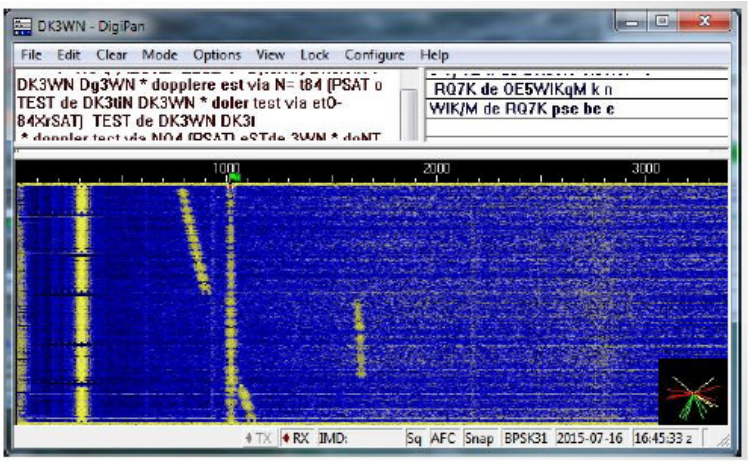
DK3WN - DigiPan
File Edit Clear Mode Options View Lock Configure Help
DK3WN Dg3WN * dopplere est via N= t84 (PSAT o
TEST de DK3tiN DK3WN * doler test via etO-
84XrSAT] TEST de DK3WN DK3t
RQ7K de OE5WIKqM k n
WIK/M de RQ7K pse be e
1000
2000
3000
TX RX IMD: Sq AFC Snap BPSK31 2015-07-16 16:45:33 z

Figure 4. Downlink waterfall shows stations with and without Doppler.

To solve the Doppler, Andy Flowers, K0SM has written an uplink PSK31 application[8] that not only uses the satellite tracking elements to pre-adjust the uplink for Doppler, but as a separate program, allows the user to operate full duplex with his existing PSK31 software being

used for downlink. Users of this application will appear fixed in the downlink waterfall as shown in Figure 4 and are easy to decode by everyone.

This PSK31 text messaging transponder allows messaging between up to 30 modest ground stations simultaneously in full duplex. HF Uplink stations do not need gain antennas but can use a vertical omni antenna and about 100 Watt SSB transmitters because of the range-gain match of the LEO orbit geometry as shown in Figures 5 and 6.

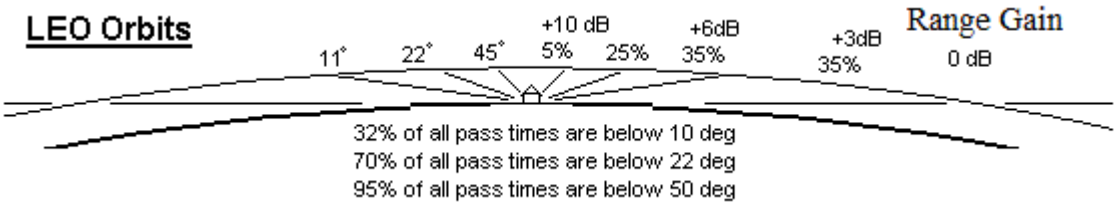

Figure 5. The LEO geometry has over 10 dB of range gain as the satellite rises in elevation.

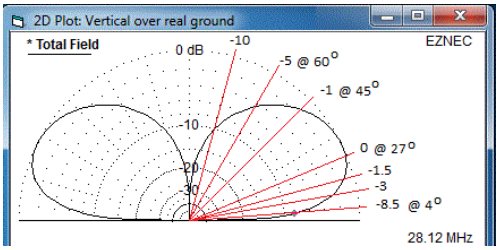

Figure 6. Typical 10m vertical antenna pattern matches the range gain of a typical LEO orbit.

The combination gives an uplink power variation per user of less than +/- 4 dB over 90% of the duration of the pass[9]. Unfortunately, however, the 6' HF receive antenna is not cross polarized as shown in figure 1 and so there will be periodic fades as the spacecraft tumbles. Figure 7 shows the challenge of getting all 4 antennas (VHF, HF & 2 UHF) to all meet at the one burn resistor.

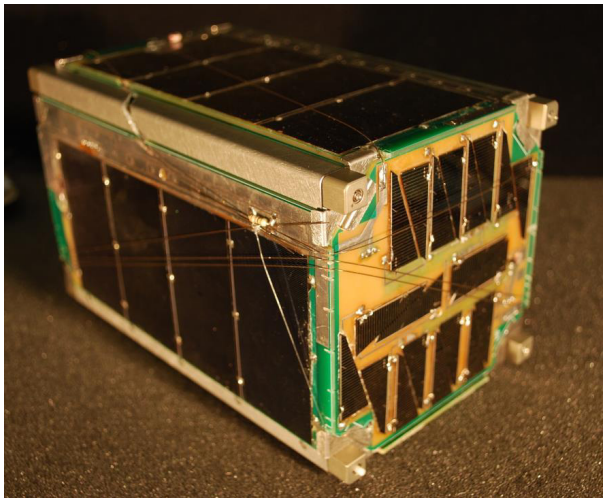

Figure 7. The UHF, VHF and HF antennas on PSAT are all released by one burn resistor.

Structure: PSAT is a 1.5 unit cubesat so that two spacecraft could be launched from the same P-Pod launcher. There was plenty of room for the Brno University PSK31 experiment. But all of the mass had to be concentrated at the center so that the spacecraft could spin about its long Z axis as shown in figure 8.

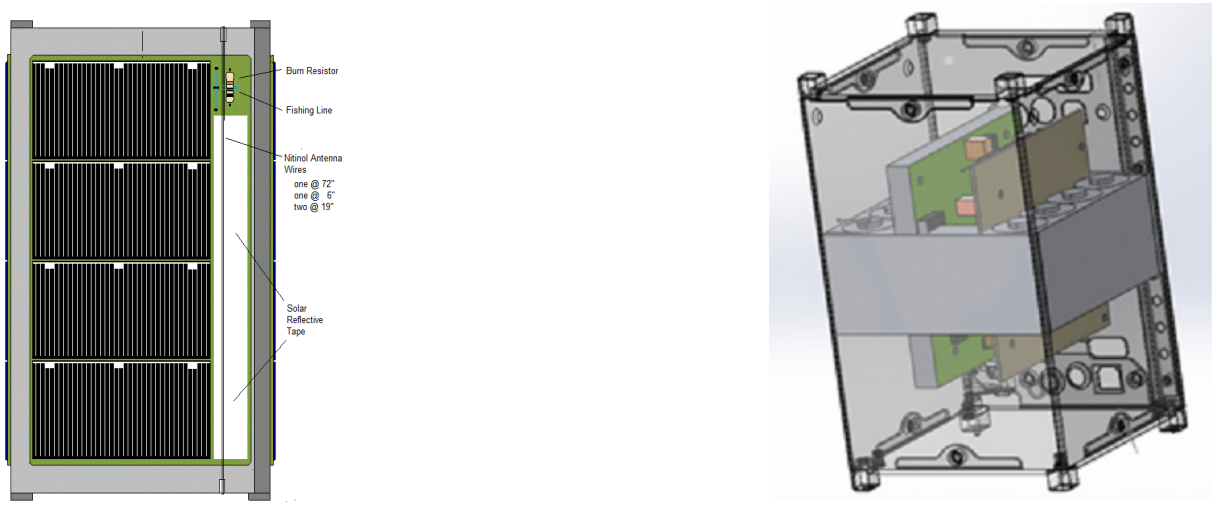

Figure 8. The sides are black/white and the mass is concentrated at the center.

Unique Power System: PSAT, with the 4 large/efficient solar cells per side is designed around a unique battery system. Since the total solar voltage per side is only 3.2 volts (0.8 volts per multi-junction cell) we can only charge two NiCd cells per side. These 4 side-panel/NiCd-pairs, that are separately charged in parallel, are operated in series for a total 9.6v bus. This parallel charging reduces the failure mode of uneven charge balance that accumulates when entire strings are charged in series. But it requires the spacecraft to spin for even charging.

The offset color pattern on the side panels uses differential solar radiation pressure to spin the spacecraft. Once a minute PSAT sends an easily readable Sun vector telemetry in its S# packet shown in figure 9. Here, PSAT is spinning about Z at a little over 2 RPM with the Z panel pointed relatively evenly at the Sun.

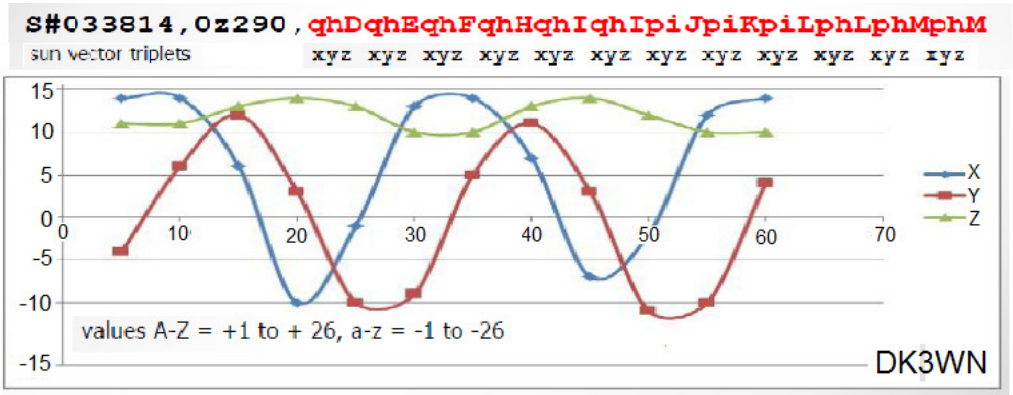

Figure 9. PSAT spin data consists of alphabetic XYZ triplets that are easy to plot.

Spin Data: But we have no control over the spin. The initial tip-off rates from the deployment soon decayed to as low as 0.2 RPM but then during a season of full sun, began to spin up to a high of 11 RPM before returning to a nominal 2.5 RPM as of this writing. You can see from the design that the maximum spin torque is when the Sun is broadside. But the higher spin momentum keeps the spacecraft in that orientation while the orbit precesses and the sun is no longer perfectly on the side and so the spin decays.

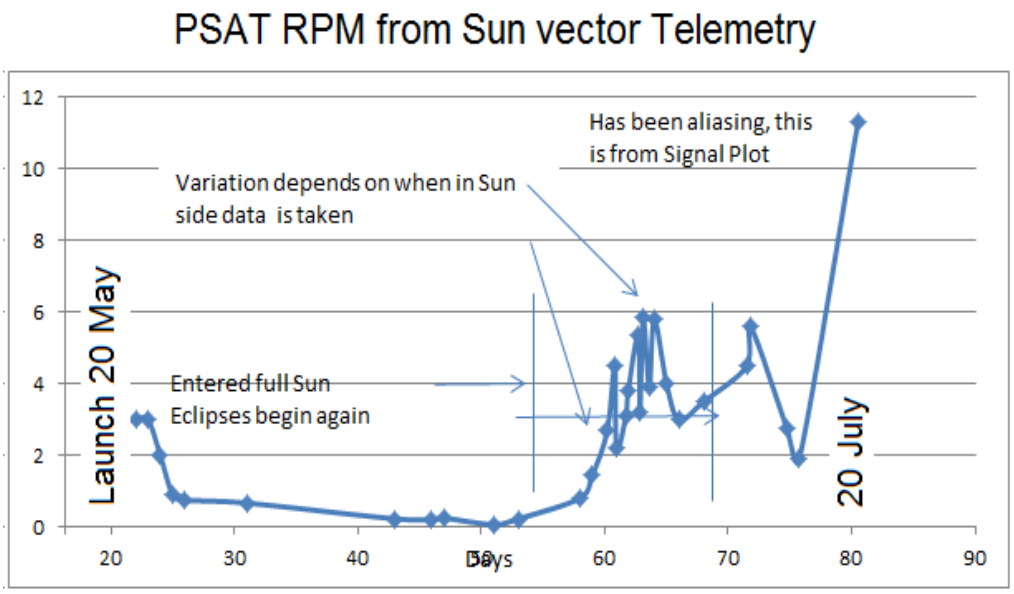

Figure 10. PSAT spin varies according to its alignment with the sun.

QIKCOM-2 – APRS for Everyone: QIKCOM-2 not only includes the APRS digipeater for those with APRS radios, but it also includes a DTMF uplink receiver for users with only a radio and keypad so that everyone can participate. The DTMF user stores his callsign and grid in a DTMF memory and can send it at the press of a button when the satellite is in view. The spacecraft not only converts this DTMF report into an APRS packet on the downlink so the user is included in the APRS network distribution, but also the spacecraft repeats the message in Voice so that all of the DTMF-only users can hear what is happening.

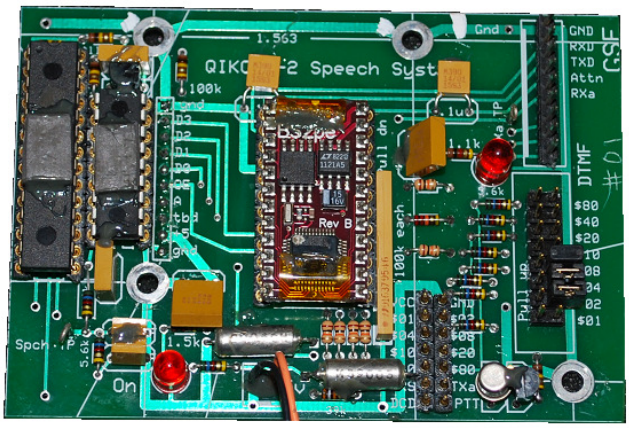

Figure 11. DTMF/Speech board on QIKCOM-2

The DTMF is received with a Byonics DTMF microreceiver and DTMF decoder chip and then converted to APRS and speech with the DTMF/Speech board shown in Figure 11 consisting of a BS2pe Basic Stamp module, a SpeakJet voice synthesizer and a text-to-speech processor chip.

DTMF Format: What makes all of this possible is the 16 digit key DTMF memories in most handheld radios. QIKCOM-2 can store not only the full callsign, but also the grid in only 14 digits plus the starting * and ending # key. The grid was compressed to 4 digits by noticing that only 99 grids actually have human poplulations in them, so the normal letter part of the grid can be reduced to two digits (00 to 99) according to the Figure 11. The grid FM19 becomes 1819 because it is the 8th one in the USA(1) group.

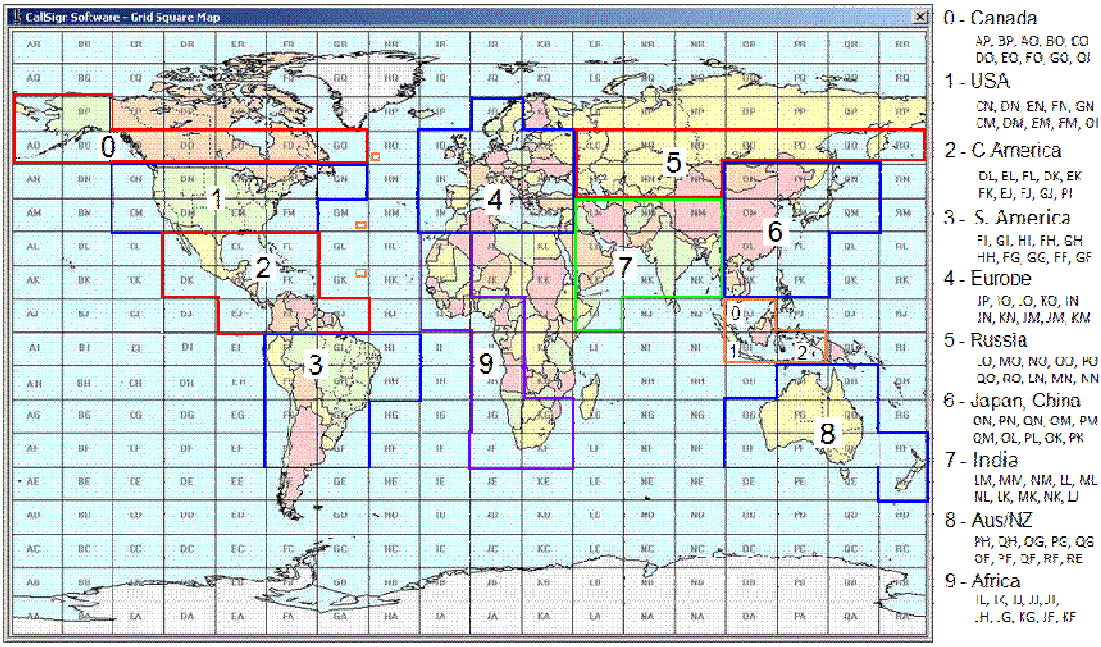
CallSign Software - Grid Square Map
0 - Canada
1 - USA
2 - C America
3 - S. America
4 - Europe
5 - Russia
6 - Japan, China
7 - India
8 - Aus/NZ
9 - Africa
The table at right begins at 00 thru 99 to give worldwide 4 digit Grids for the next APRSit DTMF satellite using DTMF only

Figure 11. The 99 populated grids can encode all of the XX populated lettered grids.

DTMF Callsign: To encode the 6 character callsign would normally require 12 digits on a DTMF key pad. But QIKCOM-2 can do it in 10. The first 6 digits are simply the 6 digits that match the letters. Then the next 4 decimal digits are the 12 bit binary number that represents 6 pairs of 2-bit representations of where the letter is on each DTMF key as shown below in Figure 12. So WB4APR is the call digits of 924277 and the location of W for example on its key is 1, B is the 2nd letter on its key, 4 is the 0th letter, A is the 1st letter , P is the 1st letter and R is the 2nd letter. So those six 2-bit locations are 120112 which are converted to decimal 1558. These 4 digits are the only digits that need to be calculated and are added on the end of the 6 digit callsign to become 9242771558. Combining that with the 1819 grid square results in the full DTMF position report of *18189242771558#.

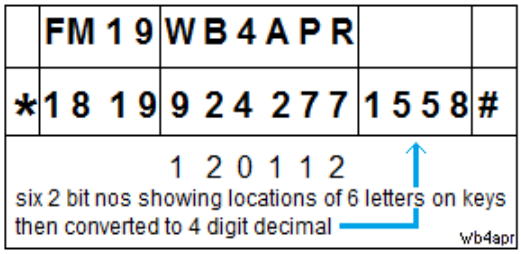
FM19 WB4APR
*18 19 9 24 277 1558 #
1 2 0 1 1 2
six 2 bit nos showing locations of 6 letters on keys
then converted to 4 digit decimal
wb4apr

Figure 12. The FM19 Grid report from WB4APR encoded into 16 DTMF keys.

On the spacecraft, this DTMF sting gets converted to a "WB4APR Grid FM19" APRS formmatted report and transmitted on the APRS downlink. Then the spacecraft says: "GRID FM19 from WB4APR". A simple report, but this communications represents a good proportion of what hams do via satellites.

DTMF Messages: But we can also send text messages! We use the trick, that most of what anybody says has already been said before. So instead of spelling out every message to be sent, we simply store the top 99 on the spacecraft and then just call them up by number. Ham radio has always used this shortcut for frequent messages in the 47 standardized ARL Numbered Radiograms [10] plus a few dozen more we have added. So we can communicate quite well with just a 2 digit message number and a 2 digit "modifier". These modifiers can be injected into any standard message that has a blank number field. Such as "1140" means message number 11 "Establish Amateur radio operations on 40 meters."

Just like the Grid report, the fully spelled out message is converted to APRS packet format on the downlink and also spoken for the benefit of all the other DTMF-only users.

Conclusion: We hope these two new spacecraft will not only contribute to better connectivity of the APRS Space constellation of relay satellites but will also excite many more hams who may only have access to PSK31 and/or their old reliable DTMF walkie-talkie. Now they too can communicate position and text messaging from anywhere on Earth.

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SatNOGS – An open satellite ground station network

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SatNOGS Project is a Network of Open Source Satellite Ground Stations, focusing on Low Earth Orbit (LEO) satellites. The SatNOGS project designs and develops a full stack of technologies to deploy a global network of ground stations including a ground station mechanical and electronic design, the receiving and transmitting (RF RX-TX) radio subsystem of the ground station and also the client and server software implementations for the Network. The technology stack design is focused on modularity and interoperability with existing ground station and radio setups.

A reference satellite ground station design was developed and documented. The design is focused on ease of construction utilizing off-the-shelf components, materials and access to rapid prototyping machinery (3D printers). Our reference design is a weatherproof Azimuth-Elevation rotator for permanent and mobile satellite operations. All designs are available under an Open Hardware license (CERN OHLv1.2) maximizing reproducibility and community engagement around the project.

The receiving and transmitting radio subsystem (RF RX-TX) is targeting radio amateur bands (2m and 70cm) implemented through custom-build circular polarization Uda-Yagi antennas, Low Noise Amplifiers, duplexers and Software Defined Radio modules.

Server and client software implementations are developed in Python (including Django web framework and pyephem library). The user experience is tailored around the needs of a satellite observer/operator offering advanced scheduling capabilities using the distributed ground stations as nodes. The Network user is able to schedule an observation of a satellite, on a specific transponder (frequency and modulation) for a specific time frame. Network then issues observational tasks to be executed by the ground stations through the Client software subsystem. All code is released under an Open Software license (AGPLv3 and GPLv3).

As part of the SatNOGS project we also deployed an online crowd-sourced database of satellite transponders (SatNOGS DB). Satellite operators, users and enthusiasts are able to submit transponder information in the database, and once approved this information is used on the SatNOGS Network for scheduling purposes. All transponder information is also available through a public API or a browsable interface, for usage by third party websites and applications.

The SatNOGS project aims to provide open access to a satellite ground station network with global coverage allowing researchers, operators and enthusiasts to obtain LEO satellite transmissions by recording them through continuous tracking of LEO satellites in a crowd-sourced global way. As such SatNOGS is able to accommodate the tracking needs of CubeSat

operators providing seamless access to a multitude of ground stations hosted by CubeSat operators, researchers, and amateur radio enthusiasts alike, deduplicating ground station operation efforts.

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DEPARTMENT OF SCIENCE AND TECHNOLOGY (DOST)
& UNIVERSITY OF THE PHILIPPINES (UP)

AMSAT-PHL

Nanosatellite and Amateur Satellite Ground Station Development Activities at the University of the Philippines

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[September 7, 2015]

Abstract

The Philippines, being a disaster-prone country, relies on datasets from satellites for a multitude of remote-sensing applications. In response, its Department of Science and Technology (DOST) supported the Development of Philippine Scientific Earth Observation Microsatellite (PHL-MICROSAT) program with the aim to build, test and launch the Philippines' first earth observation satellite while developing capacity through deep, intensive study leading to the actual development of important satellite technologies. One of the paths that a team of students, instructors and engineers at the University of the Philippines (UP) Electrical and Electronics Engineering Institute (EEEI) have taken is the development of nanosatellites and the formation of AMSAT-PHL. This paper describes some of the accomplishments of the team in the development of its own amateur satellite ground station and the roadmap for its nanosatellite development.

Background

Despite its rich natural resources and genuine allure, the Philippines' geographic location in the Pacific has made it one of the most disaster-prone countries in the world. Filipino scientists spend great amount of money buying images from commercial satellites for better urban planning, flood control,

resource mapping and weather forecast. These images are not only expensive, but are also limited in terms of quality and quantity. Moreover, the overhead between date of order and delivery makes it unusable for time-critical applications such as disaster response. In response, the Department of Science and Technology (DOST) supported the Development of Philippine Scientific Earth Observation Microsatellite (PHL-MICROSAT) program with the aim to build, test and launch the Philippines' first earth observation satellite. It addresses not only the need for relevant and timely satellite data for remote sensing applications, but also the need to develop capacity through deep, intensive study leading to the actual development of important satellite technologies. PHL-MICROSAT-1 is a joint effort between DOST, the University of the Philippines, Hokkaido University and Tohoku University in Japan.

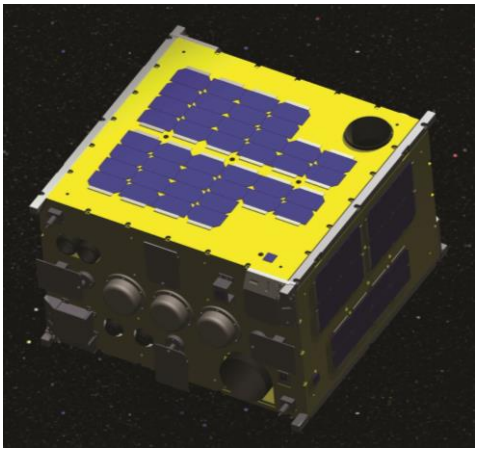

Figure 1. A rendition of the 50-kg microsatellite, PHL-Microsat-1 [1]

Microsatellite and Nanosatellite Development in UP EEEI

While the bulk of development work on the first microsatellite is being done by Filipino engineers and scientists in Japanese partner universities, the local team in UP EEEI is investigating possible incremental improvements that can be implemented in future microsatellites. Some of our activities at UP EEEI include the following:

- Exchanging ideas and collaboration between Japanese experts and Filipino graduate students in Japan
- Parallel activities to contribute in the design of some component blocks of Philippine microsatellites such as radio transceivers and antennas
- Short-term trainings
- Facilitate the establishment of the local Microsatellite Research Laboratory
- Development of undergraduate and graduate courses in small satellite technology

Moreover, DOST tap the expertise and experience of Mr. Leo M. Almazan in developing nanosatellites and satellite ground station. Mr. Almazan previously worked for the US Department of Defense, Space and Naval Warfare Center (SPAWAR) in San Diego California and is also ham enthusiast. Being granted as a DOST *Balik* Scientist [2], Mr. Almazan has been guiding students, instructors and project personnel in building and operating an amateur satellite ground station. He also shares his knowledge and practical experience at SPAWAR on creating nanosatellites such as cubesats and tubesats. As the *Balik* Scientist's host institution, UP EEEI provides technical personnel support (such as students,

researchers, and faculty), as well as facilities and equipment in wireless communications, RF, mechanical, electronics and instrumentation among others.

AMSAT-PHL Ground Station at UP EEEI

As a simple yet significant entry point, the team decided to put up an amateur satellite ground station. The ground station development provided entry-level engineers in this field an opportunity to learn about the existing amateur satellites; learn to track and make QSOs; and work on development projects such as automation of frequency control, antenna position control and design of antennas. The team sees their work on amateur satellites as an avenue for learning research and development, test procedures, components and algorithms intended for a bigger, more expensive multi-unit satellite (e.g. 2U/3U micro-satellite).

One of Mr. Almazan's notable contributions is the formation of a Working Integrated Product Team (WIPT) and teaching its systematic way of tackling projects and organizing its people. A Program Development Plan and Schedule (PDPS) were developed and subsequent WIPT meetings and design review involving the stakeholders were held in accordance the PDPS.

The block diagram of the AMSAT-PHL ground station in Figure 2 is one of the initial outputs those meetings and design. The ground station is designed to house an AC power distribution and conditioning system. The system is intended to improve the quality of the power that is delivered to electrical load equipment and provides "clean" AC power to sensitive electrical, analog and digital equipment. It provides surge protection, voltage regulation as well as noise filtering for the ground station. In addition, the ground station houses a server and storage for both immediate and future use of AMSAT-PHL. Using a satellite tracking software that is interfaced to controllers, the amateur transceiver can be automatically tuned to compensate for Doppler effects and the antenna rotator can trace the real-time position of the satellite in orbit. The list of equipment is summarized in Table 1, most of which are still under procurement. Meanwhile, the team is learning more about the inner works of a station by improvising and developing our own alternative for some of the still unavailable equipment.

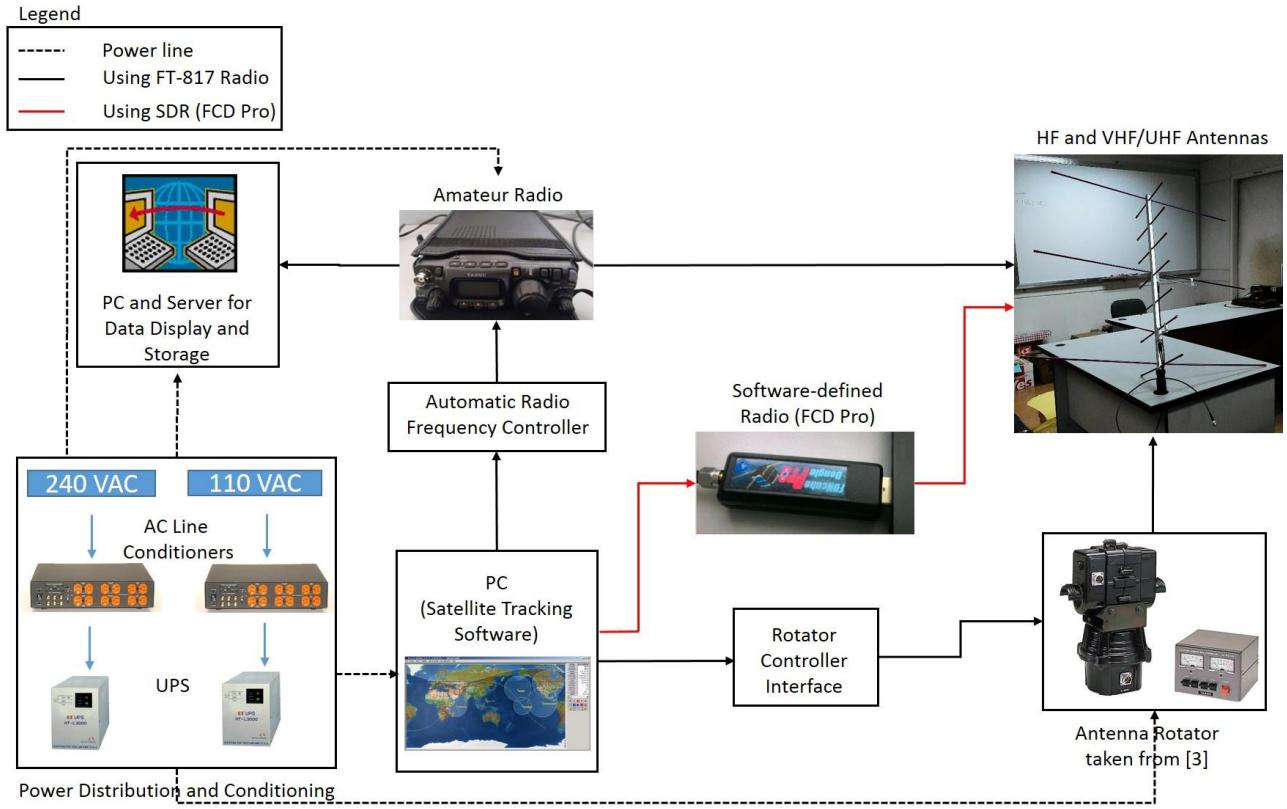

Figure 2. AMSAT-PHL Ground Station System Block Diagram

	DESCRIPTION	PURPOSE
ICOM 9100/YAESU FT-817	HF/VHF/UHF Transceiver	Main ground station radio
ALINCO DR 635T	Dual Band VHF/UHF Transceiver	Backup radio
BAOFENG UV-5R	VHF/UHF Handheld Transceiver	For portable demo and operation
FUNCUBE Dongle-Pro+	Multiband SDR	SDR investigation
CUSHCRAFT A14820T	VHF Cross Yagi	Main VHF antenna
CUSHCRAFT 416-TB	UHF Cross Yagi	Main UHF antenna
ARROW II	Handheld VHF/UHF Satellite Antenna	For portable demo and operation
CUSHCRAFT A-3S	20/15/10M HF Yagi	Main HF antenna
YAESU G-5500	AZ/EL Antenna Rotator	Main antenna rotator
YAESU G-450	AZ Antenna Rotator	For HF antenna
SIGNALINK USB	Digital/Voice Mode Sound Card	Multimode digital unit

Table 1. Ground Station Equipment List

Having HF/VHF/UHF and emergency power capabilities, the ground station equipment can also be used for emergency communication purposes, especially if the conventional communication facilities become unavailable due to disasters or calamities. The amateur satellite station is currently housed in one of the rooms in UP EEEI and will eventually be part of the soon-to-be built Microsatellite Research Laboratory.

The UP EEEI Team successfully tracked satellites with the following:

- Satellite tracking software: NOVA and SatPC-32
- Yaesu FT-817 HF/VHF/UHF transceiver
- VHF/UHF log periodic array antenna
- VHF/UHF cross-yagi antenna
- FunCube Dongle (FCD) Pro+ [4]
- Antenna rotator azimuth control using PIC microcontroller
- Automatic Transceiver Frequency Control
- Power Supply and Filter/AC Line Conditioning system

Figure 3, shows the FunCube Dongle Pro+, a relatively inexpensive software-defined receiver. During testing, it was observed that the SDR has relatively lower sensitivity than the bench-top Yaesu FT-817. We also discovered that the UHF and VHF bands in our location are quite noisy, mostly coming from terrestrial stations and other radio equipment in the vicinity. The team is still working on possible solutions to overcome this situation. Nonetheless, the team was still able to record the HO-68 CW and AO-73 BPSK transmissions using the FCD Pro+. A screenshot of the received signal from HO-68 is shown in Figure 4 at around -70 dBm.

Figure 3. Funcube Dongle Pro+ Software Defined Radio

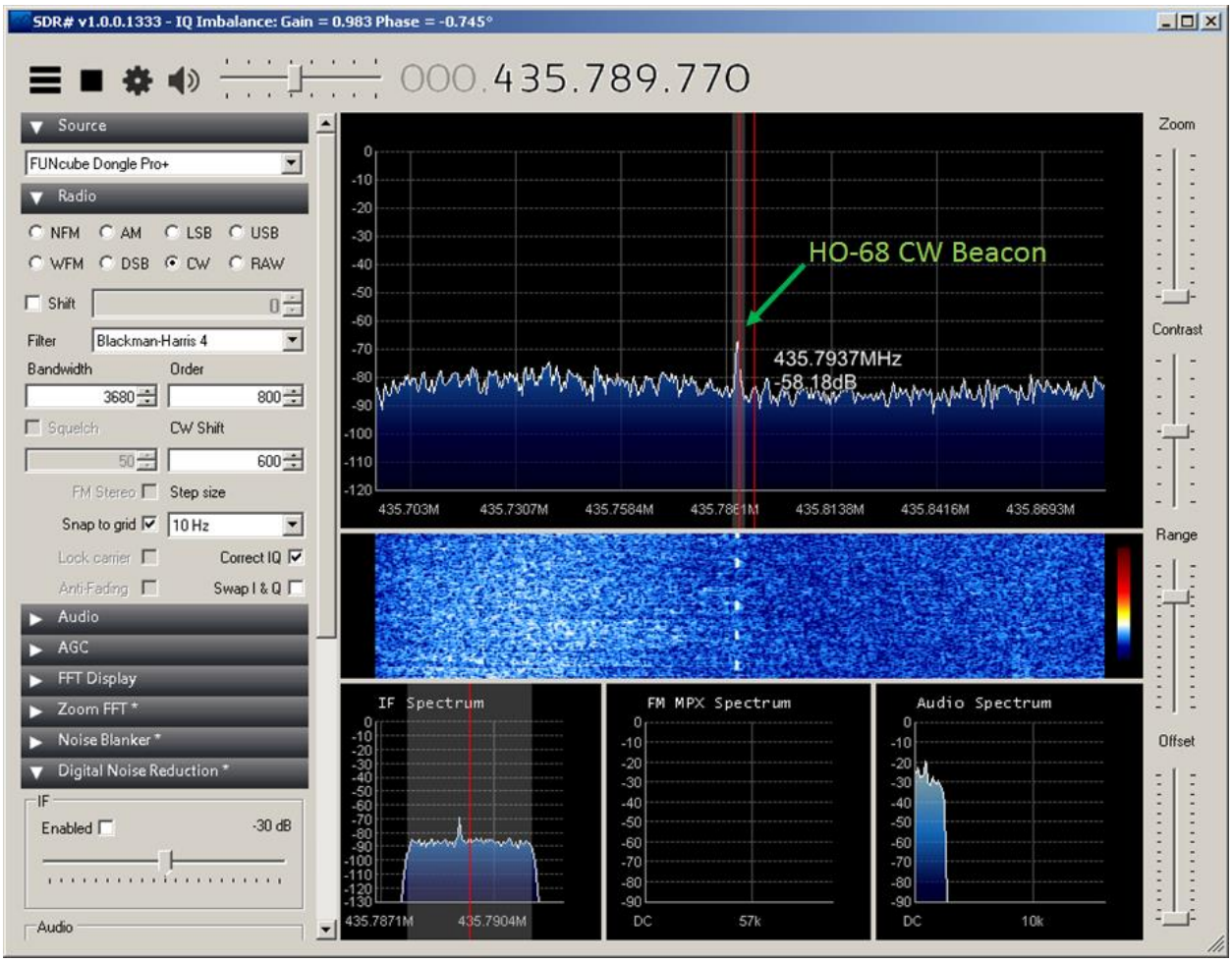

Figure 4. HO-68 CW signal being tracked using FCD Pro Plus

The team designed and fabricated a system based on the Skyking SU2000 and Nova's Easycomm I data format, which will position an antenna matrix remotely using either manual controls or from information calculated by a satellite tracking software. The system consists of a PC interface, a switchboard/motor driver circuit, and an azimuth rotator (currently being expanded to AZ/EL antenna rotator). A PC interface/driver using a PIC microcontroller was developed and successfully tested (shown in Figure 5). The system is now being expanded to work with other rotator models for both AZ/EL controls. A prototype is shown in Figure 6.

Figure 5. AZ Antenna Rotator PC or Manual Control Unit

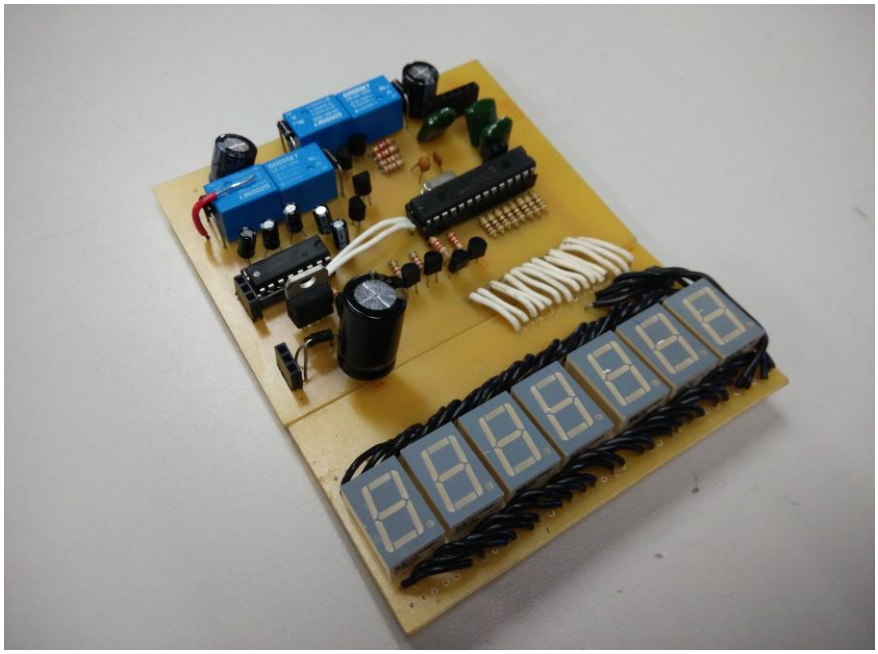
Figure 6. Two-axis (AZ/EL) automatic antenna rotator board

Furthermore, a student developed a microcontroller interface for the Yaesu FT-817 [5] that collects and uses data from the SATPC32 program to automatically control the frequency of the receiver. This is shown in Figure 7. As the frequency changes due to Doppler shift, the microcontroller adjusts the frequency tuned in by the radio. The microcontroller board connects to the FT-817 via the ACC jack, and to the computer via a usb-to-serial (RS232) interface.

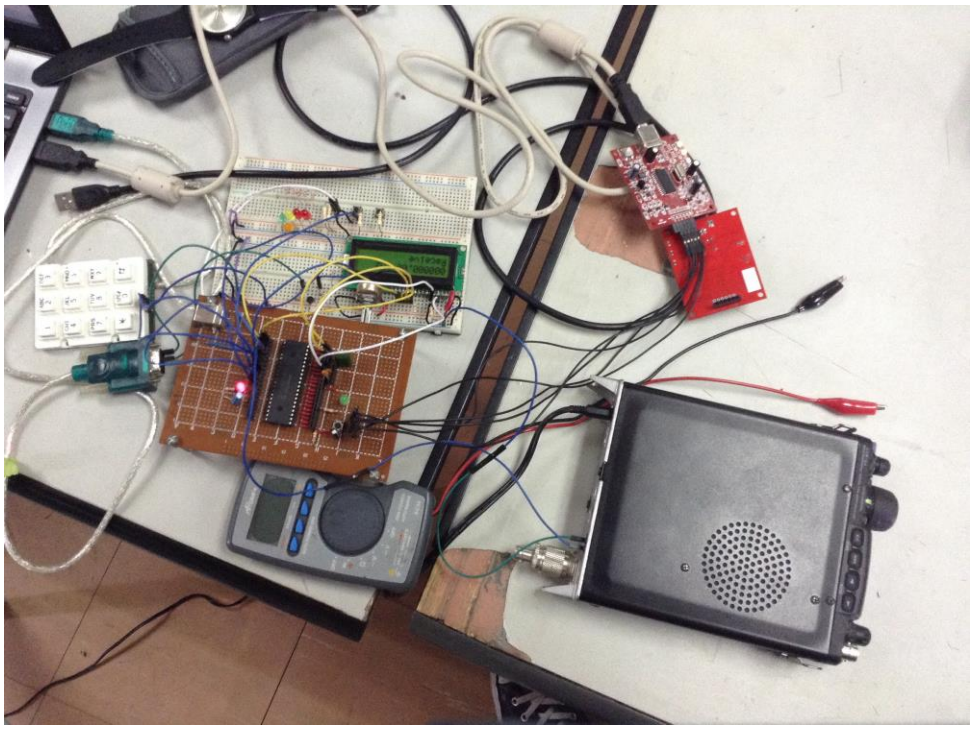

Figure 7. Microcontroller interface for the automatic frequency control (and Doppler adjustment)

Another student developed a homebrew paddle key for the FT-817, shown in Figure 8, to practice CW transmission. Lastly, students investigate on the design of a circularly-polarized cross-yagi antenna. Circular polarization is preferred over linear polarization to increase chances of receiving and making contact while the satellite moves in orbit. To date, the students are still working on the best compromise between desired gain, bandwidth, radiation pattern and deployability through CAD simulations.

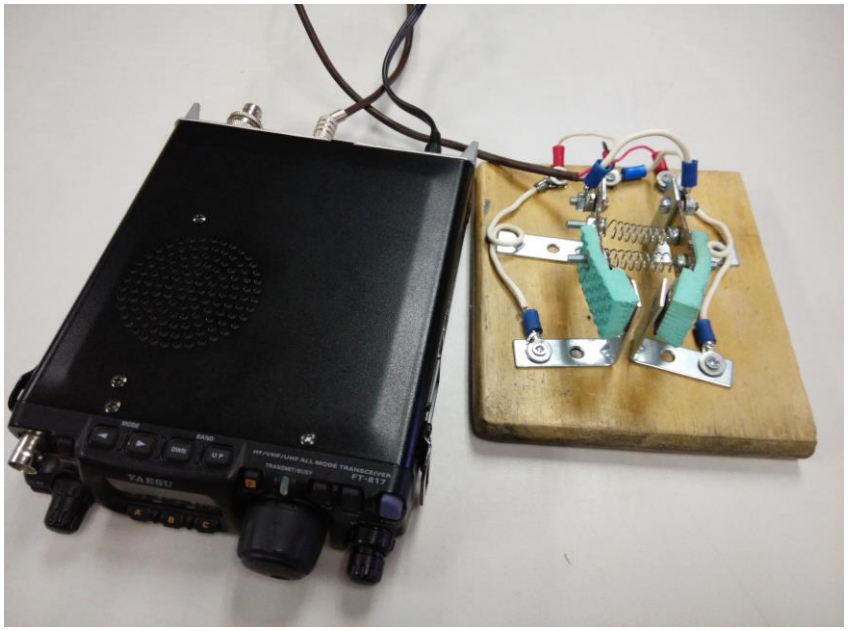

Figure 8. Homebrew paddle key for the FT-817

In summary, while Filipino engineering students are learning to build and launch PHL-MICROSAT-1 in Japan, another team in the Philippines is learning amateur satellite development in parallel with smaller cubesats. In the process, the local team is establishing an AMSAT-PHL while finding ways to effectively utilize amateur radio, especially in times of disasters – something that has real value for its citizens all over the archipelago. After this system is successfully integrated and tested, the next step is to share the skill to others in different parts of the Philippines (especially the disaster-prone areas) and have them replicate our system for their own benefit.

AMSAT-PHL Cubesat Lecture Series

With the concurrency of Dr. Joel Marciano, PHL-MICROSAT Program Leader, Leo Almazan developed a Cubesat Lecture series as part of the UP EEEI continuing education for engineering students who are interested in learning about micro and nanosatellites. An outline of the course is shown below:

I. CubeSat Introduction
    A. History
    B. AMSAT
        1. AMSAT-NA
        2. JAMSAT
        3. AMSAT-PHL
    C. CubeSat
        1. Past
        2. Current
        3. Future

II. CubeSat Development
    A. CubeSat Kit
        1. CubeSat Kit Manufacturers
        2. Basic CubeSat Kit Subassembly
            a) Airframe
            b) Electrical Power
                - Batteries
                - Solar Panels
            c) Flight Computer
                - PC/104 Standard
            d) Sensors
                - Instrumentation
            e) Attitude Control
                - Magnetorquers
                - Reaction Wheels
            f) Telemetry
                - APRS

g) Communication Unit
   - Uplink/Downlink radios
   - Antennas
h) Development Boards
i) Propulsion
   - Propellant
   - Braking system

III. Integration
   A. Design Documentation
   B. WIPT
   C. Hardware/Software

Configuration Management

IV. Testing
   A. Test Plan
   B. Test IPT
   C. Lab Testing
   D. Environmental Testing
      1. Temperature
      2. Vibration

V. Launch
   A. Launch Plan
   B. Scheduling

AMSAT-PHL Cubesat Experiments

As the cost of cubesat kits goes down, it is only natural that AMSAT-PHL embarks on the procurement of cubesat kits that meet the PC-104 bus standard. A fully functional cubesat kit is preferred. The following sub-assemblies are required:

- Airframe 1U Aluminum panel
- RF Communication (Receive and Transmit) sub-assembly
- Combination Battery and Solar Power sub-assemblies
- Power Management Control System
- Single Board Computer sub-assembly
- Antenna sub-assembly

Since cubesats are mission specific, it is important for the team to keep track of the development risks and avoid over-specification. With the guidance of Mr. Almazan, the team studied cubesat options including costs, delivery and best value.

Many possible satellite launch bases that are now established have given universities and colleges the opportunity to launch their cubesats. In the U.S., there is the NASA Cubesat Launch Initiative (CSLI) to carry cubesats as auxiliary payloads on space mission. Another company called NanoRacks uses their cubesat deployer onboard the International Space Station. NanoRacks has a program called NanoRacks External Payload Platform (NREP) where a cubesat is transferred to the ISS Exposed Facility complete

with power and communications and attached to the cubesat payload. The cubesat is then exposed to the full vacuum and radiation of an earth orbit. Data could then be collected and stored onboard the cubesat and then transmitted to a ground station. Another interesting company is Interorbital Systems, located in Mojave Desert, California, which not only sells cubesat kits but also includes the launch in the package. An IOS cubesat kit [8] is shown in Figure 9.

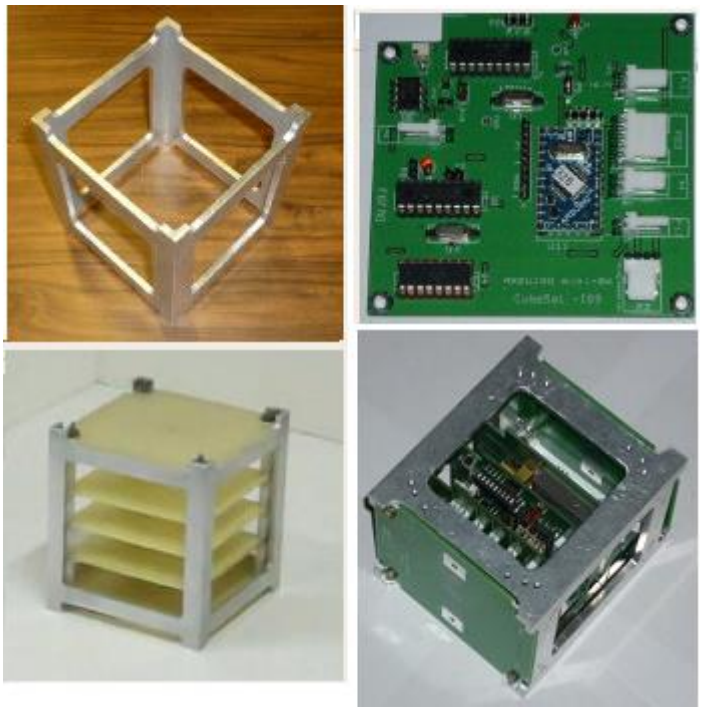

Figure 9. Cubesat kit from IOS [8]

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Virginia Tech and GEO, HEO, and LEO. We are Not University of Surrey YET. BUT WE ARE AMBITIOUS!

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ABSTRACT

In this paper we show AMSAT what Virginia Tech brings to the partnership as codified in our joint MOU. We also review how we got here and the joint work between Virginia Tech's Hume Center and AMSAT.

1 VIRGINIA TECH

Virginia Tech is a land-grant school and a polytechnic institution located in the Blue Ridge Mountains of Southwest Virginia. Founded in 1872 as the Virginia Agricultural and Mechanical College, it was immediately named Virginia's land grant college as defined by the Congress in 1862.

Virginia Tech became the Virginia Agricultural and Mechanical College and Polytechnic Institute in 1896. Almost immediately it began to be called Virginia Polytechnic Institute.

In 1892, the same year the first Masters degree was awarded by VPI, an oddly shaped ball made out of pigskin was purchased for under $1.25 (a luxury at the time) and VPI football was born.

In recognition of its increased importance, scholarship, and impact, it was renamed Virginia Polytechnic Institute in 1896 and we adopted the motto Ut Prosim, which is Latin for "That I May Serve".

VPI rapidly grew and added many buildings with the local limestone known today as "Hokie Stone". Every building has its exterior adorned in the same way (see Figure 1).

This name (VPI) was formalized in 1944 by the legislature but in a move backwards, women were moved off campus to Radford College, which was called Radford College, Women's Division of Virginia Polytechnic Institute. And Virginia marched forward smartly to prove that separate but equal did not work for women any better than it did for other groups. Radford is a fine institution and Virginia Tech is coed, integrated and a part of the modern social fabric of our nation as is Radford.

Figure 1 Burruss Hall (Administration)

In 1921, VPI admitted women. They were second-class citizens, not allowed to participate in The Bugle, VPI's yearbook but the university continued to be dominated by two things: it's commitment to

teaching, service, and community outreach and its military young men's training college, the omnipresent cadets. The young men, almost all, wore and went to class in uniform. Even today, well over a thousand students, co-ed now, are members of the cadets. It instills discipline, and provides community service opportunities and peer pressure to do well while they live somewhat segregated from much of the rest of school. It is not so much a fraternity as it is a large society on campus for the emotional support, leadership training, and mutual support, and has someone acting in loco parentis (the commandant). It sets a tone for and molds the character of the student body. They are campus leaders and want to be in charge of their lives. The University motto is Ut Prosim: "That I May Serve".

2 SOFTWARE DEFINED RADIO, GNURADIO, AND ME

I worked for the government in a FFRDC (Federally Funded Research and Development Center) at IDA/CCR for a long time when I began to work on software-defined radio for the second time.

2.1 SOFTWARE DEFINED RADIO 1.0

Tom Clark and I started the AMSAT and TAPR joint digital signal processing project when we were on the board of directors of both organizations and DSP was the rage in defense and scientific circles in the 1980s. We started tinkering with Delanco Spry TMS320C10 boards and wrote software digital communications modems (now called waveforms) in 1986, showed how it could be used to demodulate and re-modulate, and make every day packet equipment work for Fuji Oscar 12.

http://bit.ly/1jE5hLN

We talked AMSAT and TAPR and talked to AMRAD about doing this in a big way. I admit I got tired of the slow pace and the need to make some money intervened. The Microsatellites (AO-16 through LO-19) were eating up my time as well as everyone else's time so I decided to find two partners and start an enterprise with them. We designed and built the AEA DSP-2232. My partners and I talked AEA, the corporation, into giving us a firm fixed price contract for delivery of a working unit that did many modems and could do two at once using the WOWSER 13 MHz clock DSP56001 by Motorola. That is a sad story that I will give in a few lines at the end of this section.

Before we finished the unit and delivered the final firmware ever written in the second or third release of it, Tom asked me if I thought there was any currently available mode or any conceivable amateur radio mode that I couldn't detect, demodulate, decode etc. with the DSP56001. I said no, I could do them all. I stated that the performance will not be great because of the limitations of the analog to digital converters and we agreed that AT THE TIME (before Elecraft showed us all) hams didn't know dynamic range from shooting range or that IMD was intermodulation distortion and not *In Mommas Debt*. We thought it would be novel and would sell.

We proposed the SDR in 1988 to AEA and Mike Lamb, N7ML and the late George Buxton. They said yes. And my DSP2232 partnership, almost dissolved due to differences of opinion and other matters, was re-joined by my partners to do this SDR development.

Figure 2: AEA DSP2232

George developed cancer and AEA decided to cancel the project. My team dissolved in disgust and, shortly after this, George died and this began the end of the best technical company in amateur radio. It took both of them to make it a success and they were now BOTH gone. One of my team members started a company and that was the end of all civility with the new leadership at AEA. Mike hired an unpleasant man to take over the running of the company. Mike went to live in isolation and grief in Idaho or Montana (I cannot remember which). The company's new CEO fired nearly every single developer and sued me for the rights to the DSP-2232 and return of all monies expended. I just wanted to run then. I was sick of it. I agreed to do the final release of a completely revamped set of modems for the unit and delivered, and be released from all further claims. I still have the letter of praise from the CEO. He then fired every other member of the extensive and expensive development team. He was amazingly profitable for two years and then they had NO NEW PRODUCTS. The company folded but not before Mike Lamb returned, and tried to rescue the company but was ultimately unsuccessful.

AEA sold off its assets to Timewave and others and closed their door. But Tom and I had proposed a software radio to the only amateur radio manufacturer who had the vision. And it was gone in 1988. Dr. Joseph Mitola, "father of software defined radio and cognitive radio", published in 1992 what is claimed to be the first unclassified paper on software radio.

Joe is now my friend and one of the founders of my company Federated Wireless which we founded with Dr. Jeff Reed and Dr. Charles Clancy both at Virginia Tech. We love working together and exchanging ideas.

But Joe did not report or did not know of the many papers in the amateur radio publications and he certainly didn't read the description of the work that got the Dayton Hamvention 1991 Technical Achievement Award that I received for AMSAT, TAPR, and DSP work.

I dropped out of amateur radio and got really into work from 1991 until 2002. I was essentially out of the lives of my former ham friends. I was tired from all the hard work and despondent I had let my family down with the AEA failure. I did good work for ARINC (and Rick Hambly) and it led to the invention of "ACARS constructed using satellites on L band". But I was done with ham radio for a while. I no longer participated in ham radio contests and vanished mostly from my friend's lives. ***Amateur Radio Need Not Apply*** was where I was in this period and all my gear gathered dust.

2.2 RETURN FROM MY JOURNEY AND INTO THE NEXT PHASE

I returned from my nearly 11-year journey in 2002. I had worked with Tom and Rick in the past part of my life during 2000 and 2001 and used what we did effectively. But when I returned home in 2002, I was tired and had no goals or direction for my efforts. I watched and waited to see if anything interesting was going on in ham radio. I didn't really find what I needed and I looked at QEX in the Fall of 2002 at a QEX I hadn't bothered to read and saw "Software Defined Radio for the Masses Part 1" by Gerald Youngblood. And my new life, the one that led me to Virginia Tech, was born.

http://bit.ly/1M2UPZr

During this period I worked with Frank Brickle, AB2KT, on software defined radio kernel, DttSP, that was targeted at the amateur radio legacy transceiver market. Its goal was to replace the old analog stuff with a drop in replacement in software. We succeeded in talking Gerald into believing that we would develop the code and with the support of IDA, my employer, we did just that.

2.3 GNURADIO (say whaaaat?)

During this period, I became interested in GnuRadio and became a developer and learned the players and made important contributions. I contributed code, expert analysis of code, started using GnuRadio at work, and was noticed by the powerful in the US Government. I was "**asked**" to join Dr. Charles Clancy at the Laboratory for Telecommunications Sciences of the University of Maryland by the director and director of research of a major US government agency. My job was to take what he was doing and make some products *using it*.

I went to Laboratory of Telecommunications Sciences at the University of Maryland in 2006 and worked with Dr. Charles Clancy, and he introduced me to Dr. Jeff Reed of Virginia Tech who was the author of the most popular software defined radio text for universities at that time. We had a terrific time and we did great work. In late 2007, we were asked to take a trip on a US Navy ship where we were testing our work and this was completed in May 2008.

When I returned, I returned to a completely changed status in my personal life, and I essentially moved to Maryland and lived in the University of Maryland University Center Marriott or with Tom and Elizabeth Clark. They were and are like family. I miss Elizabeth terribly but Tom and I are the best of friends still. I stayed with them so much they hung a sign on a door of the room I always stayed in. They called me Bob like all ham friends and welcomed me with open arms. And to lighten the situation the door laughingly carried a sign that said:

BOOB's ROOM (sic)

The work with Charles continued apace until 2009 when he was told he needed to take another assignment to insure his advancement. He was marked for greatness by the powerful.

They sent him for months overseas to a war zone. I had lost my friend and I could tell when he returned, he wasn't happy. There were good people coming in so I decided to also take a different tour.

I went to Oak Ridge National Labs in Oak Ridge, Tennessee. I loved it but I knew it was temporary. I did interesting work and was very busy. During this time, a friend of mine from high school who had shared the same homeroom every year for twelve years told me my first girlfriend was footloose and fancy free. My friend, though about the same

age, was her aunt. That began the final step towards my move to Virginia. I didn't want to return to New Jersey. My life there was over. Sharon was not going to leave the South. Hmmm, maybe she would if I live in Virginia.

During the time at IDA in 2008, I met Tom Rondeau. He was a graduate student at Virginia Tech. He was clearly a superstar and we did work together on GnuRadio. I told Tom that when he finished his Ph.D. to please apply to work at IDA and we would do interesting work together. He did. I talked the director of IDA into hiring him as they knew I was likely to leave if they didn't give me quality people to work with as I was making a lot of noise with our sponsor with Dr. Charles Clancy. Charles and I led a major effort on Software and Cognitive Radio research and planning during the summer of 2008 in Princeton. Now it was Dr. Tom Rondeau reporting to work.

Rondeau won the 2008 National Council of Graduate Schools Best Ph.D. Thesis of the Year award for his work on Cognitive Radio. In 2009, before I left to go to Oak Ridge, Tom discussed with me his plans/goals and he knew that GnuRadio needed new leadership. Many of us worked to make that happen but it was clear only Dr. Clancy and I were actually making the decision. We had effectively taken over management of GnuRadio and we had made a great tool of it. Dr. Rondeau was and is now the leader of GnuRadio Software Defined Radio Framework.

I left and went to Oak Ridge and then looked for my next act. Charles told me Virginia Tech was looking for a director. He told me he was applying. He got the position and I told him if I got an offer I would come there as his deputy and I would live in Blacksburg and be the on campus presence while he worked in Arlington and became known to all of our myriad government sponsors.

3 HUME CENTER FOR NATIONAL SECURITY AND TECHNOLOGY

3.1 Early days

In late 2009, alumnus Ted Hume and his wife Karyn endowed the Hume Endowment with the goal of establishing programs at Virginia Tech that would prepare students for careers working in national security with the goal of cultivating and sustaining a pipeline of top-notch talent ready to hit the ground running in careers working for defense and intelligence agencies and their contractors. Virginia Tech formed the Ted and Karyn Hume Center for National Security and Technology and the Bradley Department of Electrical and Computer Engineering provided a faculty position for its director.

Simultaneously, Virginia Tech received a $2.5M grant jointly with Howard University as an Intelligence Community Center for Academic Excellence. This provided funding for student outreach programs and curriculum development in national security.

These factors all came together with the formal launch of the Hume Center in April 2010, with Jeff Reed named the interim director. Charles Clancy joined in July 2010 as the Center's Associate Director, based in Arlington, VA. A formal kick-off ceremony was held in August 2010

3.2 Early Days

With the launch of the Hume Center in 2010, a search for the director began. For the first year, the Center operated lean, drawing on some startup funds from the endowment, and began working with a number of intelligence agencies to develop a few key major programs. By mid-2011, Charles Clancy was named Director and Bob McGwier, N4H,Y joined as the Director of Research to oversee the growing research programs in Blacksburg. In October 2011, the research partnership with L-3 Communications was executed, which accelerated the initial growth of the Hume Center. I actually competed against Charles for center director. Thank goodness he got it because I won. I get to direct all of the technical staff and technical work and now that I have half way grown up, I am good at telling others what to do!

From 2011 through 2013, the center increased in size ten-fold. Mark Goodwin joined as Deputy Director. The Hume Center sustained and grew its relationship with key intelligence agencies.

3.3 Too Big for our home? ICTAS CENTER

In late 2013, the Hume Center was reorganized into an ICTAS Center. ICTAS is the Institute for Critical Technologies and Sciences at Virginia Tech.

http://www.ictas.vt.edu

This and other adjustments to our financing gave our center the necessary resources to scale, including significant real estate and staffing expansion. Dave Levy and Jon Black joined as Associate Directors of Research to provide additional leadership to technical research investment areas.

In October 2014, the education partnership with SAIC was executed, accelerating its undergraduate

engagement programs, scholarship programs, and curricular and extracurricular activities.

4 AEROSPACE SYSTEMS

AMSAT won a NASA Elana and I wanted to bring VT into the project so I begged, borrowed, and stole and used my Research Slush fund to start while I convinced Hume Center Leadership that we should be in Aerospace in a big way and, that if they let me run free, I could start VT on the path to being a major spacefaring university, maybe big enough to rival Cal Poly. With the government relationships we have, which are growing rapidly, and with many friends and colleagues at Aerospace Corporation and other for profit organizations, we could rival Cal Poly in the university world quickly. I want to be a university known, world wide, as a place to work with if you have a spacecraft you want built inexpensively, quickly, and that we were reliable.

I learned some valuable lessons. Master's students, no matter how good or how dedicated initially, are at a school for two very intensive years and then to get out and get a job. I will never put a Master's candidate on the critical path to success in an aerospace engineering job unless IT IS their Master's thesis. I will use part time Ph.D. students as well as part of the time of members of my technical staff.

Dr. Eric Patterson came to Virginia Tech the year after I did. I knew he did classified work for the US government and had come from ARL at Penn. State. He knew I dominated classified work at Virginia Tech and, in fact, is home to all of the highest level of work at Virginia Tech. I offered to make him affiliate faculty in the Hume Center and he said yes. We started figuring out ways to collaborate and he tells me, I am hiring a young firebrand in spacecraft systems.

Dr. Jonathan Black came to us from Air Force Institute of Technology. He is a ball of fire and keeps me running. He is upbeat, always has his head on straight, and it is always about we and never about I with him. He is a good person and a super smart one. I asked him on his first day in Blacksburg to become Associate Director for Aerospace Systems. I knew that I was simply not scalable because I was barely going to be able to get done the one and only effort I had attempted at Virginia Tech and that was a camera for Fox 1A. We didn't make it.

http://bit.ly/1KTvRJH

http://bit.ly/1OQslhH

Fortunately for us, Jerry Buxton N0JY is a new Vice President for Engineering and as he took over from Tony he found he was lacking AMSAT types with much experience, very few steely eyed rocket men less than 75 who wanted to be involved and who still have the fire in their belly for this stuff. He found me and we worked through the difficulties. I explained to him the lessons I had learned and that I would find replacement people if he moved the camera from Fox 1A to Fox 1C and that I would also do a flight spare.

4.1 AMSAT MOU and ITAR

AMSAT has been decimated by ITAR. We are not the only aerospace entity to tell the US government that they were being killed by ITAR. There were extremely powerful Senators who levied billions of dollars in unfunded mandates on commercial companies and increased contract costs to federal contractors in their rage against President Bill Clinton. This was because friends of his at an aerospace company had given the Chinese government critical help in fixing a launch system that was going to carry a satellite of theirs to orbit cheaply but it was a Long March and would be an ICBM.

Congress, egged on by Aerospace competitors who wanted to stop US satellite companies from using Chinese launchers (cheap), erected a wall so high it nearly killed all Aerospace corporations and that included AMSAT.

During the Obama first term, with Leon Paneta at the helm in the Pentagon, and Don Kerr at his side and agreeing with him from his position atop the National Reconnaissance Office, declared a few seconds after Senator Kyl from Arizona retired that the former USML would be swept clean and redone. This has happened and Sonya Rowe will discuss our current understanding of ITAR and how it has changed dramatically.

AMSAT has signed a MOU with Virginia Tech that allows AMSAT to use our Office of Secure Research and Export Compliance (OESRC) to help them manage and mitigate ITAR concerns and if AMSAT works with us, we provide guidance and cover. We have a bevy of lawyers on staff and on call who have helped us walk through the changes and to tell you that if you do A, B, C, and D you are free and clear of ITAR and you do not even have to ask "Mom and Dad may I" from the US bureaucratic moms and dads.

4.2 OESRC

OESRC is our secure research and export compliance (ITAR, DFAR, etc.) and interface to university lawyers and law enforcement and security officers and more at the university. A university doing secure, restricted, classified, or ITAR or now ANY DOD work in the US live under a blanket of horrid regulation. David Brady is a nationally known and respected person leading this office. He has gathered many universities and leads their opposition to those things which make it difficult or impossible even to do research of this type on a campus. He is not our enemy, he is our close and great friend, advocate, protector, and exactor of punishment when we make mistakes but always helps fix it. This is the main reason AMSAT wants and needs to be involving Virginia Tech in many of AMSAT's programs. We are one of the few universities that do every single kind of restricted and export controlled research and our names are used in the management suites of most members of the three letter alphabet soup of the US Government.

http://www.intelligence.gov/
http://www.darpa.mil/
http://www.acq.osd.mil/rd/

DOD agencies do research and we work with many of them.

5 SPACE@VT

The Center for Space Science and Engineering (Space@VT) is comprised of a group of faculty, students and staff devoted to the investigation of the space environment. We presently include members from the Bradley Department of Electrical and Computer Engineering and the Department of Aerospace and Ocean Engineering. The Center resides in the College of Engineering.

Our mission is to provide forefront research, instruction, and educational outreach in the fields of space science and engineering utilizing a holistic approach of theoretical modeling, advanced simulation techniques, space system and instrument design, and experimental data acquisition, analysis and interpretation.

5.1 WHO IS IN IT?

The Center for Space Science and Engineering Research at Virginia Tech (Space@VT) was officially founded during the summer of 2007 within the Virginia Tech College of Engineering which is the state of Virginia' premiere engineering college.

Space@VT is an interdisciplinary research center currently with 8 faculty members, all of which have international reputation in the fields of space science and engineering. Academic appointments of Space@VT faculty members currently lie in the Bradley Department of Electrical and Computer Engineering (ECE) and the Department of Aerospace and Ocean Engineering (AOE).

Space@VT members also include a host of prominent research professors, postdoctoral research associates, graduate, and undergraduate students.

5.2 What are we doing?

The Center for Space Science and Engineering Research at Virginia Tech (Space@VT) has broad interests and expertise in the fields of space science and engineering. Research focuses include upper atmospheric science, sun-earth connections, space instrument design, space mission design, remote sensing, magnetospheric and ionospheric physics, ground-based instrument design, ground-based space weather studies, Global Navigation Satellite System (GNSS) receivers and space weather applications, computational space plasma physics, active space experiments, spacecraft dynamics and control, spacecraft design, spacecraft environmental interactions, and advanced space propulsion systems. Sponsors of Space@VT research include the National Science Foundation (NSF), NASA, the Department of Defense (DoD), national research laboratories, as well as private corporations.

5.3 What is our mission?

The mission of Space@VT is to provide forefront research, scholarship, instruction, and educational outreach in the broad fields of space science and engineering. A key focus of the research and educational effort will be the science, technological impact, and utilization of the geo-space environment. Space@VT efforts will also focus on other planetary-space environments as future scientific and engineering interests and opportunities in this direction emerge.

Space@VT strives to utilize a holistic approach to space research and space mission development by combining theory, modeling, observation and education that employ advanced computational techniques, space instrument and space systems development, ground-based instrument development, and experimental data acquisition, analysis and interpretation within a research program that fully involves graduate and undergraduate students.

Space@VT focuses on both graduate and

undergraduate education in the broad fields of space science and engineering. Space@VT prepares students to become leaders in their chosen fields whether they are in the private, government, or academic sectors. Space@VT educates University students to make important contributions to society as a whole. Space@VT also strives to work with secondary school students to increase their understanding and appreciation of science and engineering with an objective of increasing their desire to take science and engineering as a career path.

Space@VT works towards engaging underrepresented groups in science and engineering in general and space science and engineering in particular. This engagement includes providing research and educational opportunities and experiences for middle school, high school, and college level underrepresented students. Space@VT also develops joint research and educational ventures with Minority Serving Institutions (MSIs).

The vision of Space@VT is to be a premiere space research organization of international caliber advancing the broad research, educational, and outreach mission of Virginia Tech.

http://www.space.vt.edu

6 HUME CENTER AND AMSAT

AMSAT received a NASA ELANA to kick its Fox 1 series off. I immediately wanted to get into the space game at Virginia Tech. I had joined the Space@VT group (see above) and wanted to do something that would introduce me to my colleagues and give them a sense that if a bunch of amateurs working part time on a volunteer basis can do it, we at Virginia Tech can do it, too. I want to enable Virginia Tech to become a space faring university that has the potential to exceed Cal Poly, University of Surrey, and Marburg. We have tremendously talented people at VT and they needed someone with huge vision and drive. I convinced them of that even though they were sure I was crazy at times. I had done crazier things and they knew I had come to town very quickly with the massive growth of the Hume Center. We came to town with a bulldozer and a list of things to accomplish, and we built our house, paid for it, and then proceeded to cook many fine meals!

The Fox1A camera project taught me many things that Martin Sweeting learned and Karl Meinzer got around by having NO OTHER DUTIES except AMSAT-DL.

Students are there for a short time and then they move on. They are awesome talent. They have huge amounts of energy and enthusiasm but they have to take tests, graduate, and get a job. Silly spacecraft? That's your problem. All but two members of my camera team are gone. The original author of the camera software got his Master's and left for his new job. The original hardware designer, Zach Leffke, will be telling you about the great work he is doing on the VT Ground Station in these pages elsewhere. Seth Hitefield will tell you in these pages how, after Fox 1A was missed, we got Seth to begin to finish the software for Fox 1C and now Fox 1D The camera flight units are in the hands of AMSAT for inclusion.

You cannot count on a two year commitment where ¾ of it is spent in classes and the last ¼ of it is spent writing a Master's thesis. You get about a 20%, when I have time, when it is convenient, commitment. He did a fantastic job for me and he did the right thing for himself. We are here because of him but a Master's or undergraduate student will never ever be on the critical path to a space mission for me ever again.

7 HUME, MILLENNIUM, USAF, GEO, AMSAT, ARRL AND FEMA

Hume: http://www.hume.vt.edu
Millennium: http://www.millennium-space.com
USAF SMC: http://1.usa.gov/1WFCPav
ARRL: http://www.arrl.org
FEMA: http://www.fema.gov

7.1 Is that a geostationary satellite

While working on a very important project for the US Government as a subcontractor to Millennium Space Systems (hereinafter MSS) in El Segundo, CA (and a huge project for a university like Virginia Tech), I was given a tour of the factory. I saw a large cube with one face festooned with protuberances and a fully article set of wings on two opposing faces and two completely clear faces. I said to Vince Deno, president of MSS: "That looks like a GEO spacecraft. I want to know if there is available Size, Weigh, and Power and, if so, what will it take to get aboard with a rideshare payload." Deno sensed my excitement knowing the project could always use an infusion of cash. If we were simple enough to easily be included, we would almost be pure profit. I assure you, to win this USAF Wide Field of View contract, they had been forced to do lots of "cost sharing" and they did because they need to get flight heritage on their FIRST geo spacecraft. We win, they win, and in my opinion, the country wins. MSS is lean, mean, and hungry and they are a joy to work with. The USAF Is

taking advantage of their need for flight heritage to get an inexpensive vehicle and test flight for an instrument they need to derisk and get flight heritage on this instrument.

7.2 You're not the first crazy hams I have known!

The CEO and founder of MSS is Stan Dubyn. I was introduced to him when I asked Vince if I could get a ride on USAF Wide Field of View. Vince said, "If you can convince Stan to bring it to the Air Force, I bet you can if you can pay for it".

Figure 3: (L-R) Sonya Rowe Project Manager (KK4NLO), Jerry Buxton AMSAT Engineering VP (N0JY), N4HY, Franklin Antonio (N6NKF), Tom Clark (K3IO), Michelle Thompson (W5NYV), and Phil Karn (KA9Q).

Stan tells us that he was leader of SpaceDev and that Jan King (our first VPE in AMSAT) and Bob Davis (many projects for us) worked for him and they built Chipsat. He tells me that he has hired Jeff Ward, K8KA as VP Product Development. AND I learn that the Air Force Colonel from LA Air Force Base in charge of USAF WFOV got his graduate degree from Jeff Ward at the University of Surrey! I felt like all the signs, portents, and omens had aligned for this one moment.

I called the meeting with the people above to come and please meet with Stan Dubyn and MSS to show them who we are and how serious we are about spacecraft and to convince him we needed it.

7.3 RINCON to the rescue

Mike Parker, KT7D, founded a small company in Arizona, and Mike, Tom Clark and I were very early members of TAPR. I was in the last class where we were called out as "founders" at the 25th anniversary of TAPR. Mike hired everyone he could at RINCON from TAPR and has done amazingly well. He is very well known in the world I worked in. Mike could not attend the meeting in person but he dialed in by phone.

Having spoken with the current management at RINCON and them having a commercial interest in seeing the spacecraft carry some of their equipment to orbit, Mike arranged for RINCON to donate a professional brass board software radio to the project. He has set it up for our use at RINCON and he has written a paper about it for this proceeding and will give a talk at our symposium. THANK YOU MIKE, but this is not the last you will hear me speak of him except I wish to add our sincerest thanks to Mike and RINCON Research, INC of Tuscon, AZ. This project would not be ready to fly without them.

8 PHASE 3E AND THE USG (DO I HAVE A DEAL FOR YOU)

In July 2015 I went to Germany with Sharon (N1SMM) and we attended the large hamfest at Friedrichshafen, Germany. We also attended the AMSAT-DL annual meeting in Bochum. I wanted to tell them of a meeting I had attended with Charles Clancy, Mike Parker, and Jon Black at a place in the US government in the Washington, D.C. area.

I informed the government that I had possible access to a partially completed spacecraft that I was willing to take risks on their behalf they were otherwise unwilling to take if they would give the completed spacecraft a ride to orbit and allow amateur radio a place on it.

To my surprise, these senior government officials said yes and immediately came up with good ideas of what they wanted to do with it. Some I found startling, some I found interesting and startling. But it was enough to for to go AMSAT-DL and ask under what conditions they would give me Phase 3E, allow me to move it to the United States, finish it, and get it launched.

These wild ideas and unbelievable outcomes were not met with shock, resentment, or even a minute of hesitation. AMSAT-DL leadership said yes almost immediately and the imposed conditions we all agreed to: It must provide communications in the amateur satellite service to all amateurs of the world and not just serve the US government in secret. I told them I had no intention of ever coming back to AMSAT-DL and asking them for it unless I had a contract with the US government that allowed amateur radio communications to occur.

Dr. Jon Black and the Hume Center continue to work every week to make this happen. I HAVE MY FINGERS CROSSED!

9 GRATITUDE, BLESSINGS, LOVE OF AMSAT, LOVING VIRGINIA TECH

Since my early days in my prolonged teenage years that drifted well into my 20's while I was still trying to become man and put down childish things, AMSAT welcomed me with open arms. By the time I was 30, I was a member of the inner circle,a director, an engineering officer and learning everything I could from Jan, Tom, and Karl. They treated me as someone smart who needed a guiding hand.

I have spent from 30 years "doing what Tom Clark told me to do". We started DSP in amateur radio in a big way. We Federated Wireless and HawkEye 360.

10 THANK YOU

I am forever grateful to AMSAT for showing me what it means to be aspirational, for giving me a place to exercise my mind without much bureaucracy, and for giving me great friends and mentors like Tom Clark, Jan King, Karl Meinzer, Rick Hambly, Phil Karn, Michelle Thompson, Peter Gulzow, Lou McFadin, Dick Daniels, and many, many more. You have all been an inspiration, a blessing, and tolerated my MANY foibles and weaknesses and helped me to begin to grow up now that at 61, I have started the second half of my life. Virginia Tech is my home. It is full of unbelievably smart and capable people. Every day I attempt to surround myself with people that are smarter and know more than I do. I never have to look far. They took a person who had almost no outside publications and no academic standing after I left Auburn University in 1986 and gave me the rank of research professor, taking the recommendation of Dr. Vincent Poor, dean of engineering at Princeton University and others of similar rank as the equivalent of a tenure and promotion committee. There brave action was risky and unprecedented. I am and will forever be grateful to Dr. Charles Clancy, Dr. Jeff Reed, and Dr. Scott Midkiff head of the Electrical and Computer Engineering depart for taking their word that I deserved the rank and that everyone would agree shortly. I am still working on convincing the academics at VT, but progress is made every day.

Virginia Tech Ground Station Update

Zach Leffke (KJ4QLP)

1 Introduction

The Virginia Tech Ground Station (VTGS) is a collaborative effort between the Ted and Karyn Hume Center for National Security and Technology, Space@VT, the Bradley Department of Electrical and Computer Engineering, and the Department of Aerospace and Ocean Engineering. The primary purpose of the VTGS is to develop a space communications laboratory for use in curricular, extracurricular, and research activities. Funding for the project was granted by the College of Engineering in the Fall of 2014, from student lab fees, and is being disbursed by the ECE department. Progress on the construction of the facility is moving along nicely and the first of four major subsystems was brought online September 21, 2015. Construction and assembly of the remaining subsystems will be conducted throughout the Fall Semester of 2015 and into the Spring Semester of 2016. This paper will describe the overall design of the VTGS and the current status of the system. Additionally past, current, and potential future projects related to the VTGS will also be described.

2 System Overview

The VTGS is comprised of four major subsystems that collectively create RF apertures for sending or receiving radio signals in 11 distinct frequency bands (not simultaneously, mission dependant). The RF sources or targets consist primarily of spacecraft in Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO/GSO), but also includes astronomical targets such as the Moon and radio astronomy sources. The four subsystems are the 2m/70cm/23cm subsystem, the 3.0m dish subsystem, the 4.5m dish subsystem, and the NOAA weather satellite subsystem. These four subsystems are all based on Software Defined Radio (SDR) technology. Each major subsystem has band specific RF equipment such as Power Amplifiers (PAs), Low Noise Amplifiers (LNAs), band specific antennas, etc. to optimize RF performance for a specific frequency band.

In addition to the four major subsystems, the VTGS also has a number of smaller subsystems that also serve important roles, such as the Davis Vantage Pro2 Weather Station which provides local weather monitoring. This section gives a high level description of the overall VTGS and the supporting infrastructure. More details of the RF design of the four major subsystems are given in Section 3.

2.1 Site Layout

The VTGS is installed in and around the ECE Field Projects Laboratory, also known as the Tracking Station. This building and the concrete antenna pads were originally built on a NASA contract in

the late 70s to conduct RF propagation and rain fade studies using both terrestrial and satellite links. This facility is located away from the main Virginia Tech campus which offers plenty of space to work, concrete pads already installed for antennas, minimal interference from the campus wifi network (important for S-Band operations), and a gigabit fiber optic connection to the University network. The western half of the building, the three concrete pads to the west, and the tower fixed to the center of the north side of the building have been granted to the VTGS project from the ECE department. The remaining pads and eastern half of the building are in use by the Power Systems group and are unavailable to the VTGS project. Figure 1 below shows the layout of the VTGS.

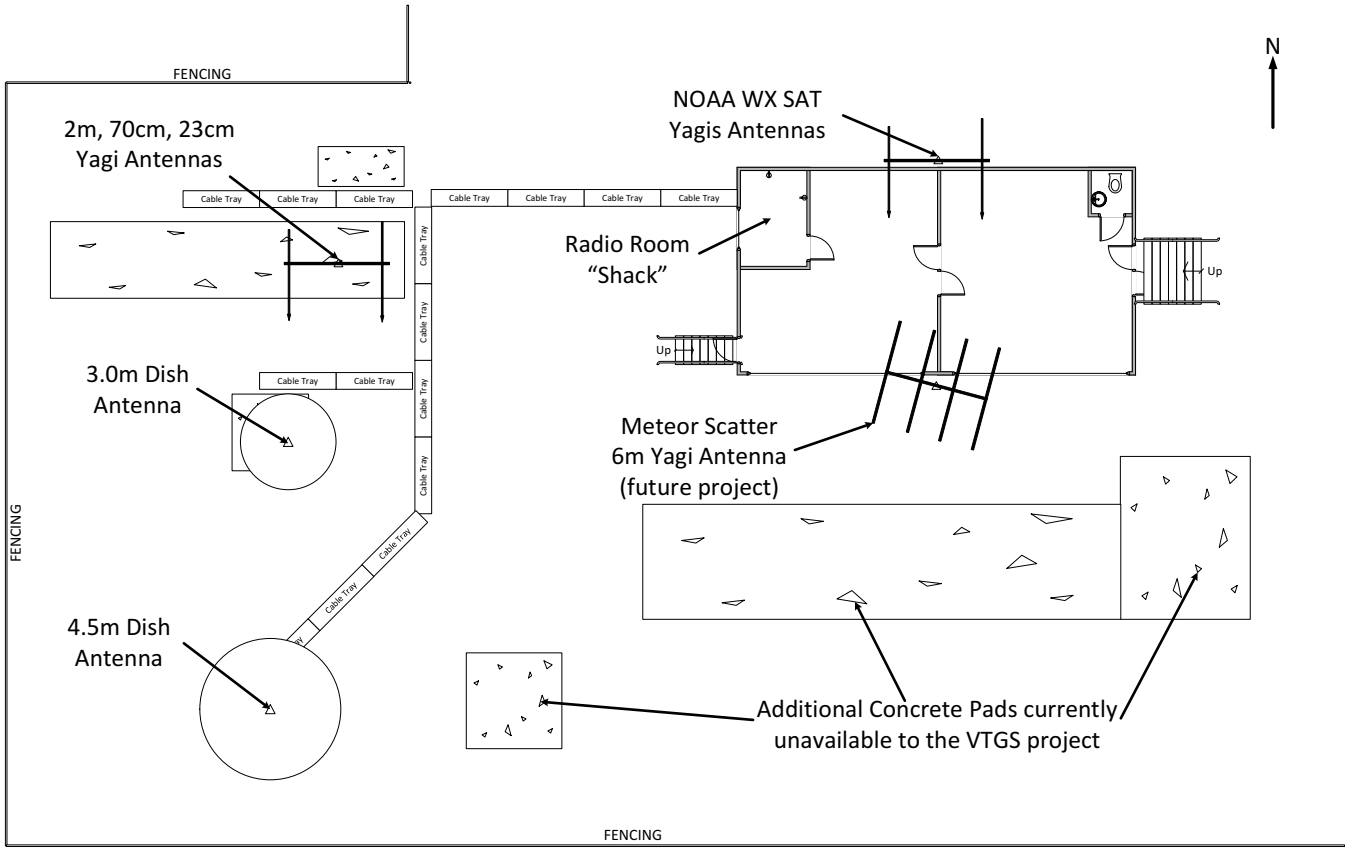

Figure 1: VTGS Site Layout.

2.2 Infrastructure

All of the major subsystems rely on the VTGS infrastructure. This infrastructure consists of multiple pieces of equipment that support the overall VTGS. The cable tray support structure provides a weather resistant routing path for all coaxial and control cables from the antenna systems back to the radio room. Inside the radio room, two 42U rackmount enclosures are utilized to house all of the equipment. The left rackmount enclosure houses the RF subsystems including the USRPs, GPS disicipline oscillator, power amplifiers, RF patch panels, DC Power Supplies, remotelly controllable AC and DC relay banks, and the legacy hardware radios. The right rackmount enclosure houses the radio servers, control servers, and tracking control units, ethernet switches, and Uninterruptible Power Supplies (UPS). A depiction of the rackmount enclosures is shown in Figure

2 below. The rear wall of the radio room holds the single point grounding (SPG) system that provides a good ground point to all of the rackmount equipment, lightning arrestors, AC power filters, and ethernet filters. The SPG is tied to the ground rod network installed in the ground around the east and north edge of the building. The majority of the spring and summer months of 2015 were spent getting all of this infrastructure assembled and in place to support the follow on subsystem installation.

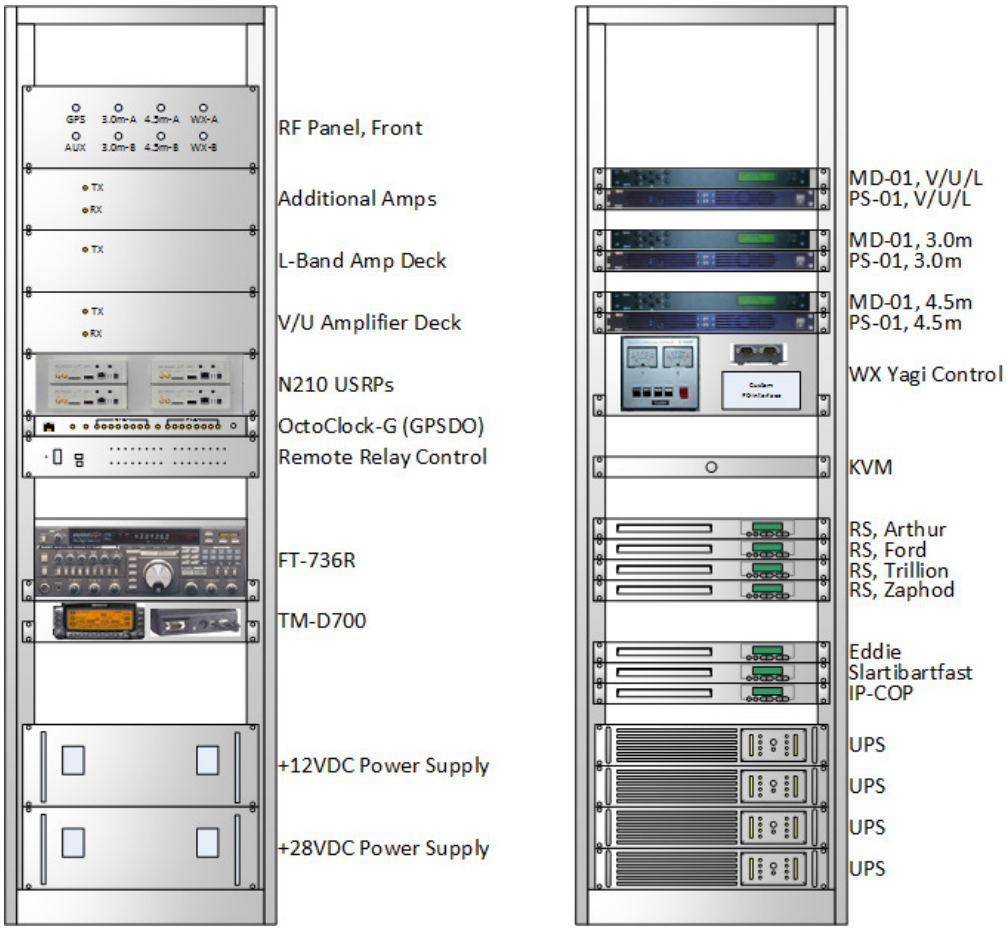

Figure 2: VTGS Radio Room Rackmount Configuration.

2.3 Network Architecture

The VTGS is intended to be utilized in multiple scenarios. This includes automated satellite tracking and telemetry downloads, remote operation by system administrators, remote operation by students using dedicated workstations, and eventually remote operation by third party entities external to Virginia Tech. Due to the complexity of serving these multiple network access scenarios, the networking infrastructure of the VTGS is fairly complex. The Tracking Station serves as the primary ingest point for the various RF signals emanating from the spacecraft that will be tracked, operated, and controlled by the VTGS. It is also the primary point from which signals will be radiated to the various spacecraft. The primary control point for the facility will be the Operations Room in the Space@VT building located in the VT Corporate Research Center (CRC). In addition to this, master control servers, data storage servers, and the public webserver will be housed in the

Hume Center offices also located in the CRC. Dedicated, persistent IPsec Net-to-Net VPN connections will provide secure connections between the Hume Center servers and the Tracking Station equipment. Individual users, whether system administrators, controllers, or student operators will access the VTGS network through road-warrior SSL/TLS OpenVPN connections. A conceptual figure of the VTGS network is given below.

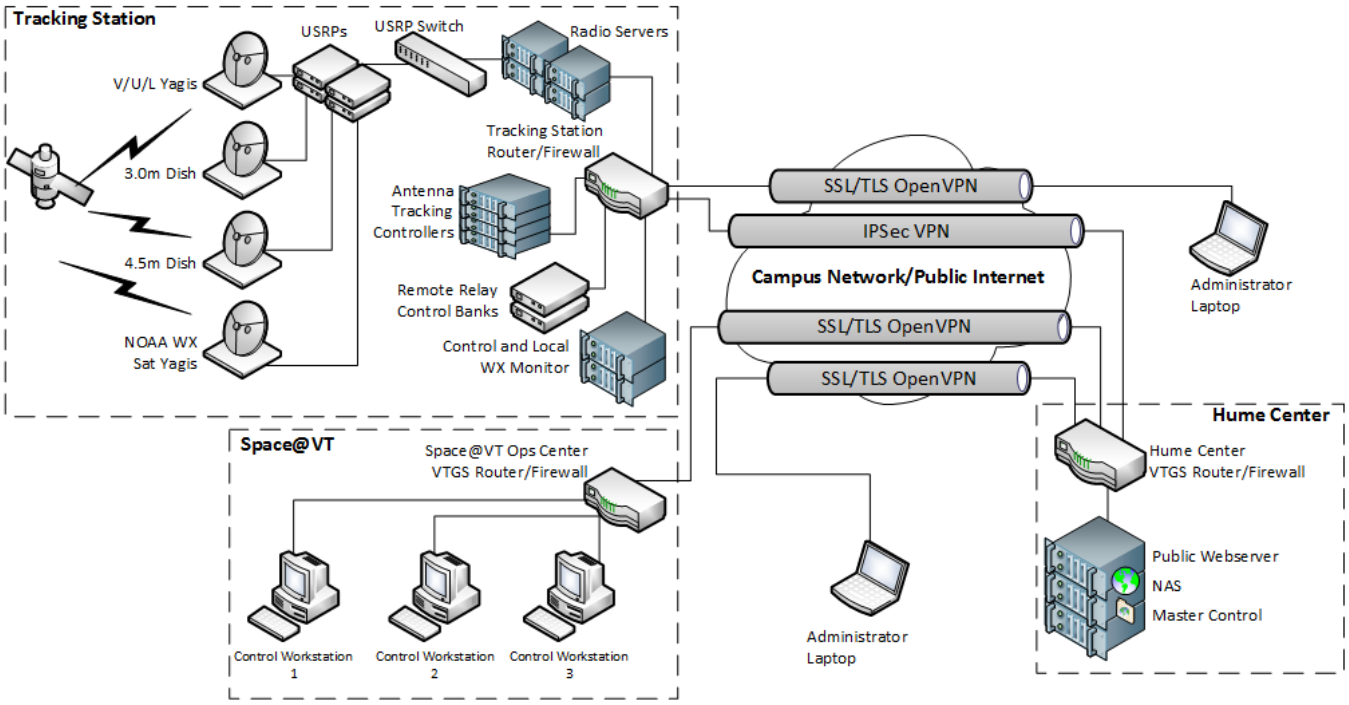

Figure 3: VTGS Network Diagram.

3 RF Subsystem Design

This section will give high level descriptions of the RF design of the four major subsystems of the VTGS. The base transceiver for each subsystem is the Ettus Research Universal Software Radio Peripheral (USRP). The open source GNU Radio software radio framework is the digital signal processing framework of choice. Specifically, a single N210 model USRP, with appropriate daughter cards, are dedicated to each subsystem.

3.1 2m/70cm/23cm Subsystem

The 2m/70cm/23cm Subsystem is the center piece of the VTGS. The majority of cubesats and smallsats that operate in the Amateur Radio frequency allocations are active in the Amateur 2m and 70cm bands. Additionally, the 23cm Amateur Satellite Service uplink only allocation is slowly becoming active again, most notably with the later spacecraft in the Fox-1 series. Figure 4 below depicts the block diagram of the 2m/70cm RF subsystem. The 23cm subsystem shares a USRP with the 3.0m Dish S-band components and more details are given in Section 3.2

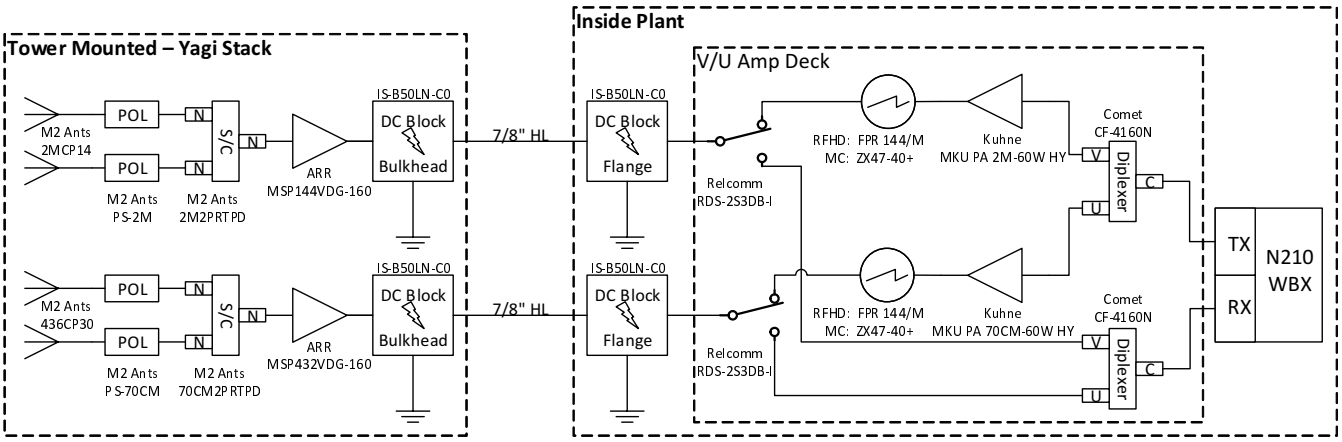

Figure 4: 2m and 70cm RF Subsystem Block Diagram.

The 2m/70cm subsystem include a pair of crossed yagi antennas for each band. These antennas each have a polarization switch which allows selection of Right Hand Circular Polarization (RHCP, default) or Left Hand Circular Polarization (LHCP). The pair of antennas are combined in phase using a power splitter/combiner. The vertical stacking of the antennas for each band provides a somewhat squashed pattern in the vertical plane, improving noise performance when at lower elevation angles compared to single long boom yagis of similar design.

The Low Noise Amplifiers (LNAs) are mounted on the T-Brace structure close to the power splitter/combiner to optimize noise performance. The LNAs are bypass capable for transmit operations and can handle up to 160W of power when in the bypassed (transmit) state. LMR-400 UltraFlex coaxial cable is used to create the rotator loop and bring the RF signal from the LNAs to the lightning arrestors that also serves as the junction point to the hardline coax. Extremely low loss 7/8" CellFlex hardline is used to carry the signal back to the Radio Room single point ground system, where the second stage lightning arrestors are mounted. LMR-400UF jumpers are used to connect the SGP mounted lightning arrestors to the 2m/70cm amplifier deck mounted in the RF rackmount enclosure. Control of the polarization switches, LNA power, and LNA Push-To-Talk (PTT) signals is accomplished through a custom built, network accessible, remote relay control box. This allows for remote power control and proper sequencing of the equipment depending on pass specific parameters.

The 2m/70cm/23cm antenna pointing is accomplished through the use of the Alfa SPID Big-RAS/HR rotator/elevator system. The HR notation denotes high resolution pointing capability for these rotators. This is accomplished through the use of hall effect sensors for the position feedback, which gives 0.2 degree pointing accuracy. The MD-01 controllers used to control the rotators have 0.1 degree resolution, and have the optional ethernet module installed for control and monitoring via a TCP/IP network connection. Custom control software has been written that implements the MD-01 protocol. Currently, this software is implemented for remote manual operation only in a simple python based control GUI. Soon the MD-01 protocol will be implemented in a headless daemon program that will run on the Tracking Station control server. This control daemon will be in charge of pointing for ALL of the antenna systems of the VTGS, and will facilitate either remote 'on demand' pointing from a human controller (in either a manual or automatic mode) as well as automated satellite tracking (no human in the loop). Figure 5 below shows the assembled 2m and 70cm antennas.

Figure 5: 2m and 70cm Antenna System.

The 2m/70cm subsystem was brought online in a receive only capacity on September 21st, 2015. FO-29 happened to be overhead when the final cables were put in place and claims the prize as the first satellite received by the new VTGS. The satellite was tracked and the 70cm downlink monitored using a spectrum analyzer-like GNU Radio application called 'uhd_fft.' Signals from the passband of the transponder were quite strong, and the system appears to be very sensitive. Figure 6 below shows a screen shot of the spectrum, and the noise generated by FO-29's passband can actually be seen in addition to the signals from operators active on the bird. Additionally, on the same day, the terrestrial APRS network was monitored to exercise the 2m side of the system and GNU Radio flowgraphs were used to monitor and decode APRS transmissions.

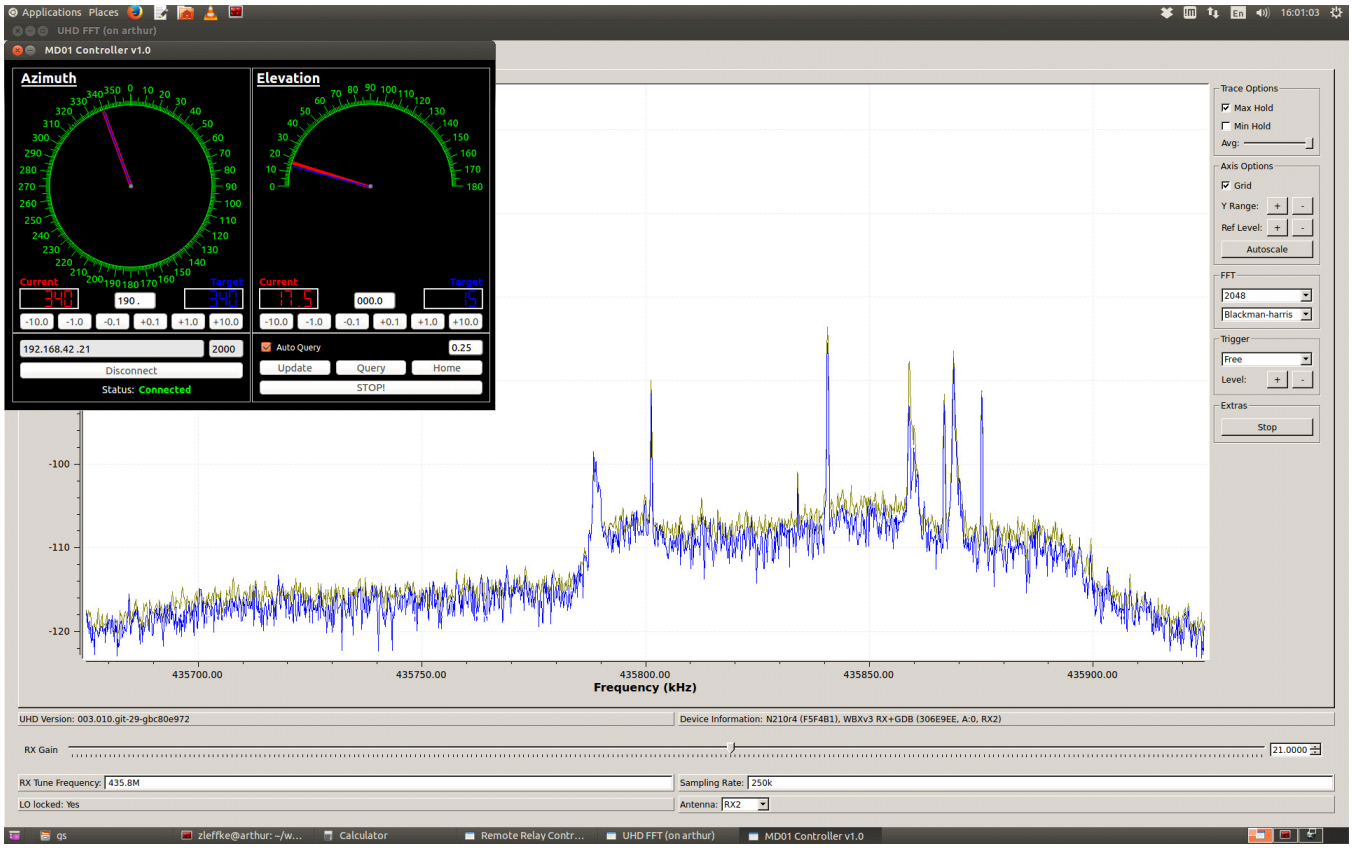

Figure 6: Spectrum Display of FO-29 70cm Downlink Transponder Passband.

Adding transmit capability is the next step for this subsystem and is currently in progress. The majority of the key parts have been acquired, and once the remaining components arrive, assembly of the 2m/70cm amplifier deck will begin, hopefully by a student under Faculty supervision. Multiple designs for the amplifier deck were considered, but ultimately a final design was settled upon that makes use of Kuhne Electronics amplifier modules. These modules are capable of achieving full 60W output power with less than 100 mW of drive power, which is a key feature due to the limited output power of the USRPs, eliminating the need for multiple amplification stages. Additionally, these amplifier modules have built in final stage filtering to ensure that the VTGS meets out of band emission requirements from the FCC. While 60W is certainly more than enough for satellite operation (in fact way too much when combined with the gain of the stacked yagi antenna systems), having plenty of extra signal power on the uplink is considered prudent by the designers for satellite *control* operations. Other key features of the 2m/70cm amplifier deck include continuous monitoring of VSWR during transmit operations, high VSWR lockout and alert mechanisms, network accessible (via TCP/IP) control and monitoring, proper sequencing during transmit, and low loss signal pass through and combining when in a receive state. Addition of transmit capabilities is expected to be finished by the end of the Fall Semester of 2015.

3.2 3.0m Dish Antenna Subsystem

The 3.0m diameter parabolic reflector antenna was purchased as a kit from RF Ham Design out of the Netherlands. This antenna is a prime focus mesh reflector, has an F/D ratio of 0.45, and has mesh spacing of 2.8mm allowing a maximum usable frequency of around 11 GHz. The quoted

efficiency of the antenna from the manufacturer is 65%, but this is dependant on a number of parameters and will be verified after assembly. This antenna was intentionally purchased as a kit as it offers a hands on learning opportunity for students, who will be helping to assemble and mount the antenna. Additionally, it offers an opportunity to learn about the physics of dish antenna systems and the importance of minimizing perturbations in the parabolic surface in order to maximize the efficiency of the antenna.

The 3.0m antenna subsystem will primarily be used for amateur S-band communications (around 2.400 GHz). Specifically, ISS Ham-TV DVB-S signals are the first 'signal of interest' to be targeted by this subsystem. Additionally, this system will be utilized for future high rate telemetry and mission data downloads from cubesats and smallsats. NASA heavily makes use of the S-Band spectrum as well, at lower frequencies around 2.2 to 2.3 GHz. Since these two bands are closely spaced, the primary feed that will be used by the 3.0m dish antenna will be a helical feed that is inherently wideband. Additionally, a Low Noise Block downconverter (LNB), purchased from Kuhne Electronics, will be utilized as the first active RF device in the receive chain.

This configuration offers a number of advantages. First, the wideband helical feed and block downconverter combination offers a receive aperture that covers two satellite bands of interest. Additionally, the use of a block downconverter at the antenna shifts the received signal to a much lower intermediate frequency (IF). This minimizes the losses along the 85ft run of hardline coaxial cable back to the receivers in the radio room. Finally, the LNB purchased from Kuhne Electronics has a low noise figure and will be mounted directly to the feed assembly to maximize the overall noise performance of the system. One downside is that the feed assembly is inherently circularly polarized and there is no option to switch polarization sense on the fly. Ultimately, this system will provide an aperture capable of receiving S-band signals from both the Amateur Satellite Service, the Amateur Weak Signal bands (around 2304 MHz) and the NASA S-Band downlink band, offering a number of opportunities for interesting student projects. Figure 7 below depicts the RF Block diagram of the wideband S-Band receive configuration.

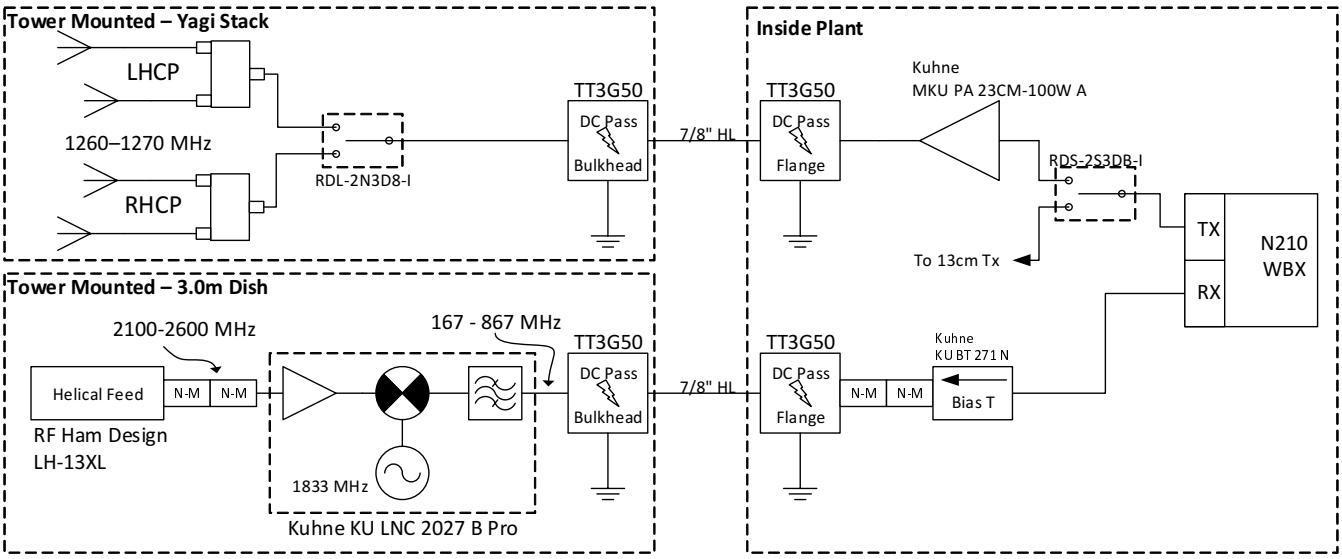

Figure 7: L/S-Band RF Subsystem Block Diagram.

In addition to the helical feed assembly, an OK1DFC-style stepped septum feed has also been purchased for this system. This feed has a much narrower bandwidth and has been factory tuned

to the Amateur Satellite Service frequencies. This feed was acquired in addition to the helical feed for two reasons. First, it serves a backup feed in case of some type of failure in the helical feed assembly. Additionally, it offers the ability for duplex communications in the Amateur Satellite Service, should a specific mission be identified, and a need for transmit capability is identified.

As mentioned in Section 3.1 and depicted in Figure 7 the 3.0m dish system shares a USRP with the L-Band uplink system. Four Loop Yagi antennas, from Directive Systems and Engineering, tuned to the Amateur Satellite Service uplink only 23cm band are utilized for this system. The physical antennas will share the H-Frame of the 2m/70cm antennas. Pairs of these antennas are utilized to generate circular polarization, two for LHCP and two for RHCP. This will be accomplished by physically mounting the antennas with a quarter wave offset along the boresight axis, with one antenna oriented 90 degrees around the boresight axis, and then combining the antennas in phase. Selection of polarization sense is accomplished by use of a high power coaxial relay mounted at the antenna. As this allocation is uplink only, no pre-amplifier system is required, and only a power amplifier is required. For the VTGS, a Kuhne Electronics MKU PA 23CM-100W A amplifier is used. As with the 2m/70cm PA modules, this device is capable of achieving full power of 100W with 100mW of drive power (max power out of USRP) and has the necessary finally stage filtering to meet FCC out of band emission requirements. This amplifier system may be temporarily re-purposed, on a case by case basis, for use with the 4.5m antenna during EME operations.

3.3 4.5m Dish Antenna Subsystem

The 4.5m Dish antenna is also from RF Ham Design and has many of the same characteristics as the 3.0m system described in section 3.2 with the obvious exception of aperture size. The primary purpose of this subsystem however is different in that it is not intended for satellite communications. Instead this system is supposed to provide an aperture to the VTGS that is reminiscent of the Jet Propulsion Lab's Deep Space Network (though clearly smaller in sclae). The two primary missions for the 4.5m dish antenna are for Earth-Moon-Earth (EME) communications as well as Amateur Radio Astronomy. The system will not be 'hot swappable' and manually swapping the feeds and RF equipment will be required depending on the project or experiment that is being conducted. Figure 8 below shows the RF block diagram of the system, with both the EME configuration and the Radio Astronomy configuration depicted.

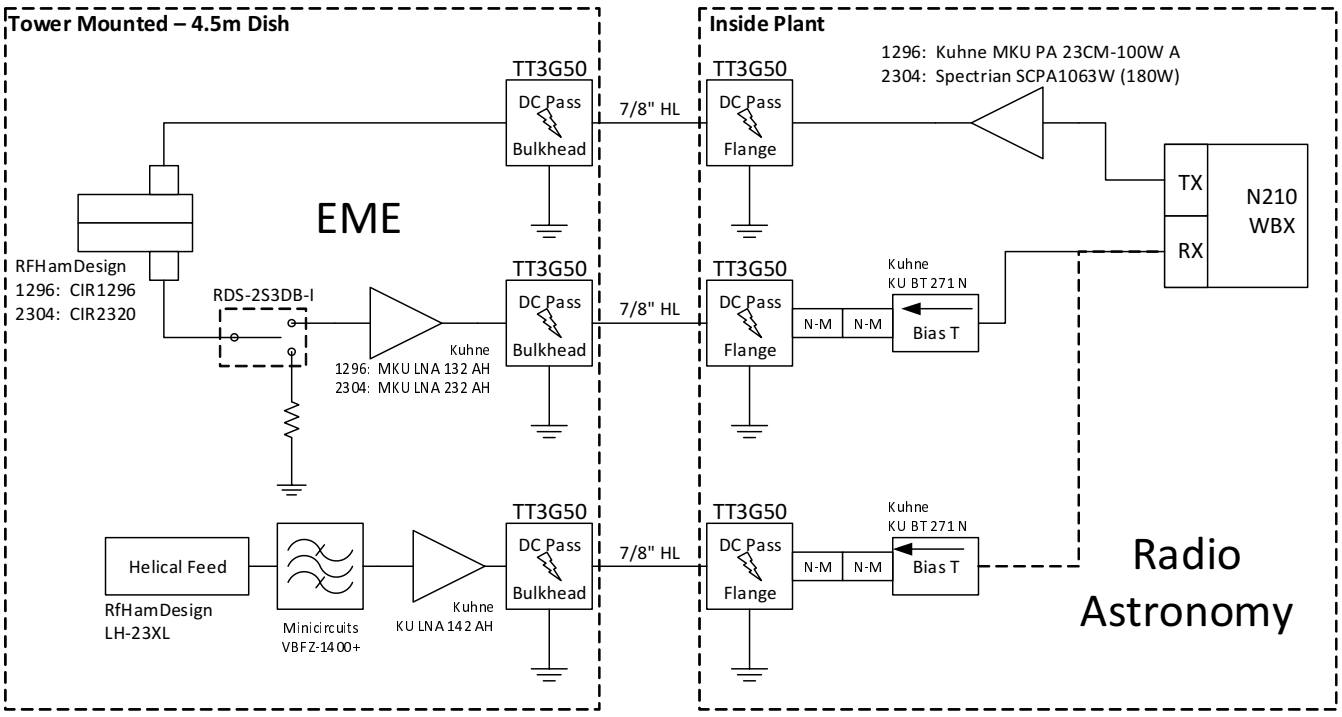

Figure 8: EME and Radio Astronomy RF Subsystem Block Diagram.

3.3.1 EME Operations

For EME operations the primary bands that will be utilized are the 23cm and 13cm weak signal or EME frequency allocations. For both bands an OK1DFC stepped septum feed will be utilized. This feed system allows for dual polarization with transmit on one sense and receive on the other. As the first goal will be to hear self echoes, this makes sense (pun intended) since the RF signal will flip polarizations when reflecting off the surface of the Moon. For operations at 23cm the Kuhne MKU PA 23CM-100W A amplifier described in Section 3.2 will be utilized. For operations at 13cm a Spectrian SCPA1063W amplifier, with 180W output power, will be utilized (to be acquired). Low noise pre-amplifiers from Kuhne Electronics will be utilized for receive amplification.

In addition to the 23cm and 13cm equipment, receive components for 3cm EME operations have also been obtained for the VTGS, including a feed assembly and a low noise downconverter. The downconverter will shift the received 10 GHz signal to a much lower 70cm intermediate frequency. While the VTGS will not be able to transmit on 10 GHz with the current level of funding, it will at least be capable of monitoring 10 GHz EME operations. An ongoing project in the ECE Integrated Design Studio, lead by Dr. Dennis Sweeny, WA4LPR, is very close to becoming active on 10 GHz EME using a 5m dish at the National Weather Service Station near the Blacksburg, VA airport. This antenna system does not allow full dome of the sky pointing since the antenna was originally intended to cover the Geosynchronous belt, and as such is mounted on a Polar mount. The design studio project will have a limited window to communicate via the Moon. It is the hope of the VTGS team to first monitor 10 GHz moonbounce attempts from the Design Studio Team. Eventually, however it is the hope of the VTGS team to merge with the Design Studio project and convince Dr. Sweeney to relocate his custom built 10 GHz transverter system and 30W Traveling Wave Tube amplifier to the VTGS for use with the 4.5m dish antenna system for TX/RX 3cm EME operations.

3.3.2 Radio Astronomy Operations

It is well known phenomenon that changes in the energy state of neutral hydrogen produce emissions around 1420.4 MHz. This is important in Astronomy as this frequency can penetrate clouds of interstellar dust that are opaque to optical astronomy. This so called 'Hydrogen Line' can be received using relatively small aperture radio telescopes. For the 4.5m antenna subsystem, feed horns, low noise figure pre-amplifiers, and filter devices have been obtained for the VTGS for the purpose of Hydrogen Line observations. An initial goal of the VTGS is to simply produce spectral observations with the newly built telescope. A next step will be to determine the the Doppler shift detected from these emissions by taking precise frequency measurements of the received signals. This is made possible since the VTGS will have a very stable frequency reference from the GPS disciplined oscillator. All of the signal processing for this will be accomplished using GNU Radio.

This subsystem is inspired by the MIT Haystack Small Radio Telescope (SRT) project, and will seek to leverage work done by Marcus Leech with respect to GNU Radio applied to radio astronomy. The VT Physics Department uses an SRT system (with a 2.4m dish antenna) as part of laboratory exercises for the graduate level Observational Astrophysics course. It is the intent of the VTGS project to augment this course by offering the 4.5m telescope for remote use by the students in this course. Additionally, members of the National Radio Astronomy Observatory recently expressed an interest in using Software Defined Radio, specifically GNU Radio, in NRAO facilities at the 2015 GNU Radio Conference. It is the hope of the VTGS team to develop a relationship with NRAO, specifically with members at the Greenbank Facility. The intent of the collaboration is to both develop practical GNU Radio receivers for radio astronomy applications and potentially collaborate on educational efforts to get students with an interest in radio astronomy hands-on experience with telescopes at VT and hopefully at Greenbank.

3.4 NOAA Weather Satellite Subsystem

The National Oceanic and Atmospheric Administration (NOAA) operates a fleet of weather observing spacecraft in both LEO and GEO orbits. The Polar Operational Environmental Satellites (POES) are in LEO and transmit both low resolution and high resolution weather imagery. The Geostationary Operational Environmental Satellites (GOES) are in GEO and transmit high resolution weather imagery. The purpose of this subsystem is to receive signals from both the POES and GOES satellites. Like the rest of the VTGS, this subsystem has a dedicated USRP and will use GNU Radio modems to receive and demodulate signals from these spacecraft. This system will be receive only, and as such only antennas, low noise amplifiers, and appropriate lightning detection are utilized (no power amplifiers). The block diagram of the NOAA Weather Satellite subsystem is shown in Figure 9 below.

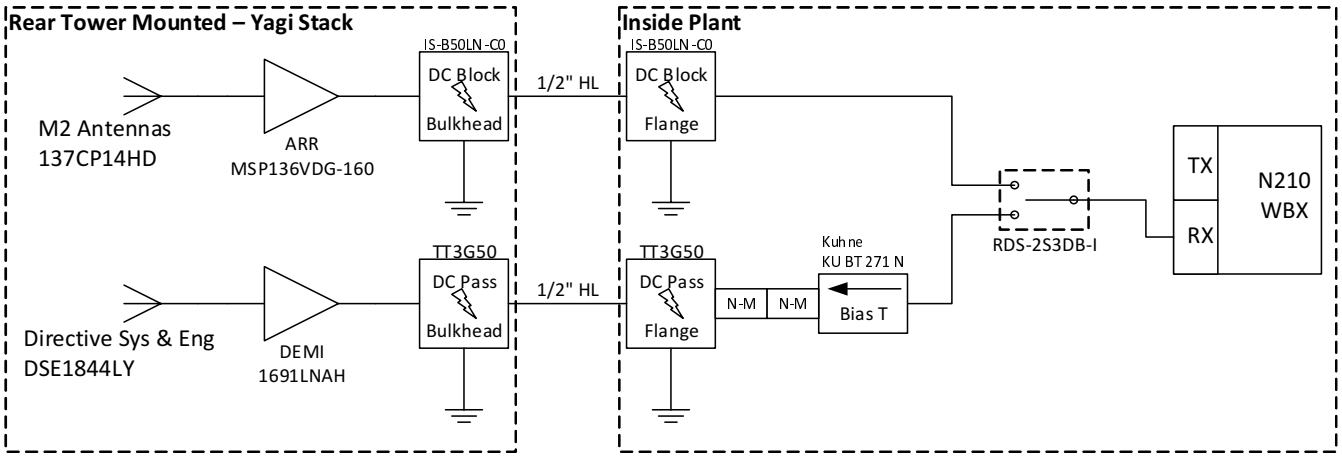

Figure 9: NOAA Weather Satellite RF Subsystem Block Diagram.

This subsystem will re-purpose much of the equipment from the prototype ground station originally built in 2011. This primarily includes the 1/2 inch hardline coax, Yaesu G5500-style rotator/elevator system, and the crossboom assembly installed on the 30 ft. tower attached to the northern wall of the Tracking Station facility. Antennas tuned to the NOAA 137 MHz band will be used to receive low resolution imagery from the POES constellation via the Automatic Picture Transmission (APT) protocol. Antennas tuned to the NOAA 1700 MHz band will be utilized to receive the higher resolution imagery available from both the GOES and POES constellations via the High Resolution Picture Transmission (HRPT) protocol. It is the intent of the VTGS team to deliver this imagery data to the Meteorology Department within the College of Natural Resources (in addition to potentially posting it on the public VTGS webserver) in order to augment existing course work.

4 VTGS Projects (Current and Future)

To date many smaller projects have been completed or considered that incorporate the VTGS. Below is a list of project ideas that we are hoping to explore as more of the VTGS subsystems come online. The projects listed have either been completed, are currently being explored, or are ideas being considered for future projects. Short descriptions are provided to give a very basic overview of the project idea. The list below is not comprehensive, but shows the range of projects being developed as part of VT's new Space communications laboratory.

Galaxy Rotation Rate via Hydrogen Line Doppler Shift

Using the 4.5m dish system described in Section 3.3 observations will be made of Hydrogen Line emitters (around 1420 MHz) in the Milky Way Galaxy. By making precise measurements of the Doppler shift of these emitters, given their locations and the location of earth in the galactic plane, it should be possible to determine the rotation rate of the Milky Way. This project is based on a similar project from MIT Haystack observatory and will hopefully be conducted with support from the Astronomy group in the Physics department.

Satellite Ranging via Linear Transponder

This project is based on the Phase III Ranging System article by James Miler, G3RUH (please see link below for more details). The basic idea is to implement the pseudo-random sequence transmission, via narrowband BPSK modulation, and the return autocorrelation using GNU-Radio in order to determine time-of-flight from a ground station location to a spacecraft. Given the time-of-flight delay to the satellite, and the speed of light, precise range measurements can be made. The ultimate goal is to integrate this system into a laboratory exercise for students taking Astromechanics in the AOE department at VT. The idea is the students will take actual range measurements of real spacecraft and then use orbit determination algorithms to calculate precise TLEs for the spacecraft.
http://www.amsat.org/amsat/articles/g3ruh/123.html

Amateur Radio Earth Moon Earth Communications

As described in section 3.3 the VTGS will be capable be capable of Earth Moon Earth communications in the 23cm and 13cm amateur bands, with an initial RX only capability in the 3cm band. As a first step, this project would seek to develop the necessary interfaces for combining GNU Radio modems with WSJT. Longer term, this project may seek to implement the WSJT algorithms directly in GNU Radio. The ulimate goal is to host student participants at the VTGS during the ARRL EME Contests (and eventually give the Joe Taylor, K1JT team a run for its money).

Lunar Ranging

Similar to the EME project as well as the Satellite Ranging project, this project would seek to combine elements from those projects to attempt to precisely range the moon. The intent would be to hear self echoes of narrowband PSK transmissions sending pseudo-random sequences. The goal would be to calculate a precise measurement of the range between the Earth and the Moon. This project could be designed to do one range measurement per day for a full year to show the varying distances of the Moon from the Earth over the course of a year.

Weather Station Safety Lockout System

The goal of this project is to use the Davis Vantage Pro2 weather station along with the Hobby Boards one-wire lightning detector to develop a safety lockout system for the VTGS. The anemometer will be used to take wind measurements, and if the wind speeds exceed safe levels for the dish antennas, they will be automatically placed in a zenith pointing orientation to minimize their wind profiles. Similarly, if lightning events are detected, the safety lockout system will automatically shut down all RF components, including the LNAs, PAs, and USRPs that could be damaged by high energy bursts from lightning strikes in close proximity to the VTGS.

NWS Radiosonde Tracking

Every day the NWS station located a few miles from the VTGS at the Blacksburg, VA airport launches high altitude balloons carrying radiosondes. The VTGS will have a high gain, steerable, antenna tuned to the NOAA 1700 MHz frequencies. It will be possible to use this antenna system to receive signals from the balloons after launch. This project will focus on reverse engineering the radiosonde protocol (using GNU Radio) and then post-process the sensor data from the balloons.

This project is intended to augment the course work of students in the Meteorology Department of the VT College of Natural Resources in the University.

VT Built High Altitude Balloon Tracking

Similar to the NWS Radiosonde project, this project would focus on supporting student built high altitude balloon projects at VT. Two teams (Project ELLIE and the Atmospheric Teaching Experiment, aka ATE-x) currently launch balloons as part of course laboratory exercises and outreach programs. This project would support tracking the balloons during launches and potentially downloading data from the balloons. The primary difference from the NWS experiment is the use of Amateur Radio on the student built balloons, including APRS for tracking.

POES/GOES APT/HRPT satellite imagery

As described in section 3.4, the VTGS will have steerable antennas tuned to the 137 MHz, and 1691 MHz NOAA Weather Satellite Bands. This project will focus on developing and optimizing modems for demodulating the Automatic Picture Transmission (APT, on the POES or LEO satellites) and High Resolution Picture Transmission (HRPT, on both the POES and GOES satellites) protocols used by these spacecraft for weather imagery transmission. Additionally, new digital modulation techniques will be replacing the APT protocol, and this project would seek to develop new modems to support this new protocol.

Monitoring NASA S-band communications

As described in section 3.2 the VTGS will have a wideband feed and LNB that should be able to receive in both the Amateur Satellite Service S-band frequencies as well as the NASA S-band downlink frequencies. This project would seek to determine what emitters are in use that could be monitored by the VTGS for specific NASA missions, and then build appropriate demodulators using GNU-Radio. This project is inspired by the ISEE-3 reboot mission.

ISS Ham-TV

This project would seek to use the VTGS 3.0m antenna and S-Band receiver system to monitor, demodulate, and produce video streams of ISS Ham-TV transmissions. The primary focus would be to develop DVB-S receivers using GNU Radio and then figure out how to get the demodulated video stream linked to Internet video content delivery services, for example YouTube. This capability would allow anyone to monitor the ISS Ham-TV video via the Internet whenever it is active over the VTGS.

QB50 Satellite Simulator

This project was completed by three undergraduate students for extra credit in ECE-3614 Intro to Communications. The purpose of this project was to develop a simple satellite simulator that received AFSK1200, demodulated to the AX.25 frame level, and then re-transmitted the AX.25 frame via FSK9600 modulation. This project was completed using a TM-D700 radio, a Kantronics KPC-9612+, a few bits of wire and solder, and a bit of python coding. The students learned about the two modulation schemes (AFSK over FM and FSK/GMSK) which complemented their

studies well in that course (where they learned the math behind FM, and were introduced to digital modulation schemes). This project also served to validate the AFSK1200/FSK9600 GNU Radio modems being developed for the QB50 mission at the time.

TLE Matching via Doppler Curve Fitting

When cubesats are first deployed, it is frequently difficult to quickly match the published TLE set for the individual spacecraft due to the proximity of the spacecraft to each other and similarities in their orbits. With known center frequencies on the spacecraft, a precise frequency reference oscillator, and GPS accurate time stamping of AOS/LOS at the VTGS, it should be possible to accurately determine which spacecraft belongs to which TLE set. This capability will be particularly useful when QB50 deploys and *50* cubesats all turn on a 70cm downlink at approximately the same time.

Solar Radio Astronomy Experimentation

A number of small 1.0m and 1.2m offset parabolic reflector antennas, along with the mounts, feedarms, and a handful of Ku-band LNBs have been donated to the VTGS. The goal of this project would be to use those antennas to make observations of Solar Radio Sources. This project would also use GNU Radio and USRPs to develop the appropriate receivers.

5/10 GHz User Terminal Development for HEO/GEO

Recently, AMSAT has announced the opportunity to return to HEO and potentially go to GEO for the first time. Both payloads for the spacecraft are anticipated to operate in the 5 GHz (uplink) and 10 GHz (downlink) Amateur Satellite Service sub-bands. The intent of this project would be to develop prototype ground terminals, again utilizing SDR technology, to communicate with these spacecraft.

Meteor Scatter Communications

A four element 6m yagi antenna was recently donated to the VTGS. The intent of this project is to get the antenna assembled and mounted on the southern side of the VTGS facility in order to participate in Meteor Scatter communications in the 6m band. Along with the asembly and mounting of the antenna, this project would seek to develop GNU Radio modems to interface with the WSFT software, similar to the EME goals mentioned before. Additionally, a hardware design goal has been put forth to have a student or a team of students develop and build a high power 6m amplifier that has on the order of 500W of output power.

QB50 Control Station, OGMS-SA

Through the Virginia Space Grant Consortium (VSGC) a partnership has been established between VT, Old Dominion University, and University Paris-Est Creteil (UPEC). UPEC is developing a technology demonstrator 3U cubesat, caled OGMS-SA, as part of the QB50 mission. However, at this time UPEC does not have a ground station to command and control the spacecraft. The intent of this ongoing partnership is to have VT and ODU act as control facilities on behalf of UPEC for TT& C of the OGMS-SA spacecraft. At this time, the planned interface between VT and UPEC is to send pre-planned commands to the spacecraft from a file generated by UPEC and

sent to VT before the scheduled pass. The VTGS will send the appropriate commands and record the downloaded data from the spacecraft to a file for transfer back to UPEC. It is hoped that real-time interfaces can be developed allowing the UPEC team to utilize the VTGS in real time (minus Internet delays), providing a 'Virtual Ground Station' capability.

Control Facility for AMSAT Operations

The intent of this project is to develop the appropriate scheduling and control interfaces to allow remote use of the VTGS by authorized members of the AMSAT Operations Team. The goal is similar to QB50 project in that authorized users will use the VTGS as a 'Virtual Ground Station' to command and control AMSAT built/owned spacecraft. This project will require the development of GNU Radio modems specific to the AMSAT spacecraft of interest, development of control software appropriate to the spacecraft of interest, and establishing the API for remote access of VTGS resources by authorized AMSAT Operations Team members.

ARISS Telebridge

A long term goal of the VTGS is to provide a telebridge service for scheduled ARISS Contacts. This will require development of appropriate voice modems for communicating with Astronauts and Cosmonauts on the designated 2m frequency. Additionally, the VTGS hopes to support ISS Ham TV transmissions simultaneously as described previously, should that system also be active as part of the ARISS Event.

5 Conclusion

This document gives a high level overview of the Virginia Tech Ground Station. The overall goal of this project is to provide a space communications laboratory to the students of Virginia Tech. The intent is to augment curricular, extracurricular, and research activities to provide a *real* hands on education experience in space communications.

At the time of this writing, only the 2m/70cm system is operational, in a receive only capacity. The next focus will be to add transmit capabilities to the 2m/70cm system. Installing the L-Band antennas in time for the Fox-1D launch will be the next priority. Then focus will shift to installing the rotators, control cabling, and RF systems for first the 3.0m and then the 4.5m subsystems. Finally, the NOAA weather satellite antennas will then be installed.

Acknowledgements

The author would like to thank the Virginia Tech College of Engineering for seeing it fit to fund this project. It is the ever present thought in the forefront of the minds of the VTGS team to deliver on the educational merit this project promises.

The author would also like to thank Dr. Greg Earle and Dr. Wayne Scales, from Space@VT, for advocating for the VTGS project when the proposal was originally put forth to the College of Engineering.

Finally, the author and VTGS team would like to thank the AMSAT community, from the leadership to the membership, for many reasons, too many to list here, and so we'll just say for being satellite wizards, smooth operators, and generally Awesome!

Virginia Tech Fox-1 Camera Software Update

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Robert W. McGwier (N4HY)

1 Introduction

One of the main goals of AMSAT's Fox-1 project is providing their university partners with reliable platforms for space based research. To support this, the *Ted and Karyn Hume Center for National Security and Technology* at Virginia Tech started building a camera experiment in 2013. This experiment occupies the top two boards in the stack for the Fox-1 *C* and *D* satellites that includes a CMOS camera capable of transmitting 640x480 pixel JPEG images of Earth. Once the spacecraft enters "high-speed" mode, Amateur Radio operators around the world can use the FoxTLM software to decode and reconstruct the images taken by the camera.

The main hardware design and initial software design was completed during the Fall and Winter of 2013 and presented at the 31st AMSAT Symposium [6]. Additional debugging and new features have been completed over the past several months to make the camera experiment flight ready. The new version of the software allows ground control operators to switch it among several different modes during flight, such as the image size and the stringency of the Earth detection algorithm.

2 Hardware Overview

The camera experiment consists of the top two boards in the stack (+Z) for the Fox-1 spacecraft (See Figure 1). All of the electronics specific to the camera experiment reside on the Experiment 3 board (second from the top), while the Experiment 4 card provides a temperature sensor, a feed-through connection for the solar panel (+Z), and additional room for the lens housing mounted on the camera board. The camera board itself contains several components including: an ARM microcontroller (STM32L1) [5], a VGA camera chip (OV7670) [3], a first-in-first-out (FIFO) image memory buffer (AL422B) [2], and an external MRAM flash memory chip (MR25H10) [4]. The flight board is shown in Figure 2 (the lens housing is absent), and a more detailed description of the hardware development can be found in the 2013 AMSAT Symposium Proceedings [6].

The specific processor used is the STMicroelectronics STM32L151ZDT6, which is a ultra-low-power, high-density microcontroller based on an ARM® Cortex-M3® 32-bit RISC core, with a maximum operating frequency of 32 MHz. It also includes 384 Kbytes of flash memory, 48 Kbytes of random access memory, and multiple I/O technologies including: USB, USART, SPI, I2C and SDIO. Table 1 shows the basic specifications of the microcontroller, and Table 2 shows the I/O bus connections for the different on-board components in the experiment.

Table 1: STM32L1 Specifications

Property	Specification
Speed	32 MHz
Program Flash	384KB ECC
Memory	48KB ECC SRAM
EEPROM	12KB ECC EEPROM

Table 2: Peripheral Specifications

Peripheral	Bus Type	Speed
MRAM	SPI	32MHz
FIFO	8-bit Wide Clocked	3.2MHz
OV7670	I2C-like	25kHz
IHU	UART	38.4kbaud

2.1 Focusing

The camera lens on the flight boards was focused through simple trial and error using mountains several miles away as a reference for the test images. These example pictures can be seen in Figures 3 and 4. Note that the closer grass and trees also appear to be in focus; this is due to the camera having a large depth-of-field that starts several inches away from the lens and extends to infinity.

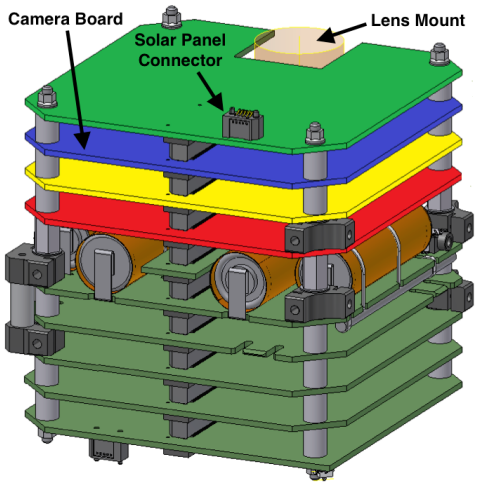

Figure 1: Fox-1 Spacecraft Stack

3 Software Overview

The software for the experiment consists of a real-time operating system (RTOS), a JPEG encoder, and the custom interface code for the camera chip, the link to the IHU (Internal Housekeeping Unit), and flash memory. The RTOS currenly being used is ChibiOS 2.4.3, which provides many features including: preemptive, round-robin scheduling; multiple priority levels; mutexes and semaphores; events; message queues; a thread-safe heap; and a hardware-abstraction layer (HAL) with STM32L1 support. A modified version of the *jpegant* library handles all the JPEG compression.

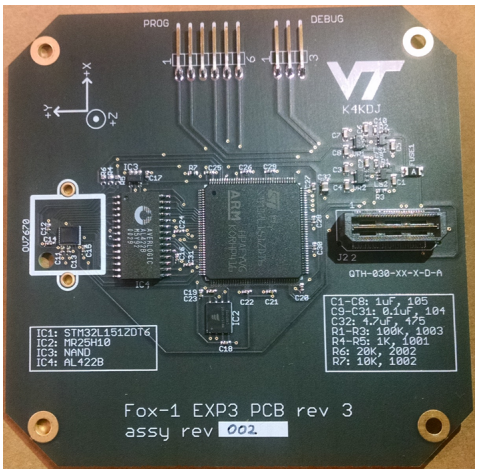

Figure 2: Camera Flight Board

Figure 3: Example Picture From Camera

3.1 Threads/Interfaces

In order to take full advantage of the multiple priority levels provided by ChibiOS and to increase the modularity of the code, the software is divided into two main threads: the camera thread and the UART thread. The camera thread handles all functions related to taking an image with the OV7670 sensor, which includes configuring the camera, reading data from the FIFO buffer, running the JPEG compression, and writing the resulting data to the flash memory chip. The UART thread handles all communication between the camera experiment and the spacecraft's IHU, including switching the camera's current operational mode (See Section 4.4), triggering the camera thread to take a picture, and transfering generated data to the IHU for transmission to the ground.

3.2 Overall Operation

Once the satellite has been commanded into 'high-speed' data mode, the IHU powers on the camera by sending an 'enable' signal on the spacecraft bus to the Experiment 3 card. Immediately upon booting, the software loads the settings relevant to the current operational mode, configures up all the required I/O interfaces and the camera, and starts taking a picture. There is no explicit

Figure 4: Another Example Picture

command required from the IHU to take the initial picture.

To take a picture, the microcontroller first configures the camera chip and then sends the proper signal to begin storing pixel data into the image buffer. Once the FIFO contains all the image data, the microcontroller can pull individual lines of data from the FIFO, compress them and store them to the external flash memory chip. The IHU periodically asks the camera if it has completed taking an image, and once ready, the camera begins transferring it to the IHU for transmission to the ground. The camera microcontroller will signal the IHU that the image has been completely downloaded from memory and then waits for the IHU to request another image (by sending another ready command). This process repeats until the camera is disabled through either a command from the ground or a timeout onboard the IHU.

4 Software Modifications

Several new features have been added to the camera software in order to make it fully flight ready. Specifically, this includes better data storage and management for the compressed JPEG lines; better control over the camera's configuration and auto adjusting levels; color/Earth detection; and selectable operating modes that are controllable from the ground during flight.

4.1 Camera Configuration

One early issue during development was determining the correct set of configuration options to use for the OV7670 camera chip. The Linux driver for the chip served as a good starting point for the default values [1].

The OV7670 camera chip has several different auto adjusted features such as exposure control, gain control, white balance, band-filter, and black-level calibration. In order to best utilize these features, the software first enables all the camera's auto settings, and takes 10 pictures that are

immediately discarded. Then, all the auto features are disabled, while preserving the current settings, and the final picture is taken.

Due to the limited size of the buffer between the camera and microcontroller, the FIFO is only able to store half of the 640x480 picture at a time. The final picture is generated in two stages with each half of the image being taken individually, compressed, and written to flash memory. This two stage approach can generate a discontinuity along the middle of the image if the camera has moved significantly between the two half images being taken by the sensor. Another solution for taking QVGA images is discussed in Section 4.4, which would allow an entire image to be stored in the FIFO at a single time.

4.2 Data Storage

Once the camera has taken a picture, the image is divided into 8 pixel high 'scan lines' and JPEG compressed. The compressed data for each line is then stored in the flash memory connected through the SPI interface. Since the maximum payload that can be downloaded to the Fox-1 IHU is 1024 bytes, memory on the flash chip is logically divided into 60 (maximum number of lines) equal length bins (1028 bytes) that consist of the line number (2 bytes), the length of the payload (2 bytes), and the JPEG line data (see Figure 5). If needed, a header, trailer, and/or checksum values can also be added to each line for checking the integrity of each line after it has been read from flash memory; however, these are not currently enabled.

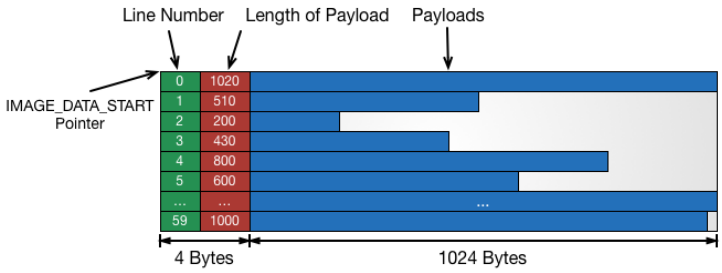

Figure 5: Layout of Image Data Stored in Memory

Initially, the JPEG restart marker (RSI) was also included as part of each line's payload, but has been removed in order to ensure the markers are not corrupted during transmission. These markers are inserted by the FoxTLM software during image reconstruction.

During processing, if the length of the current line exceeds the maximum payload length, then the rest of that line is droped and not stored in memory, which results in partial lines being rendered in the image when viewed. This behavior only occurs in very complex images that contain many hard edges; Figure 6 shows an example of these dropped lines. Due to the predicited image characteristics during flight, this behavior is not expected to be an issue. Pictures of the Earth should have far fewer hard edges that some test images, which should result in shorter payloads and more complete images.

After each line is transfered to the IHU, it is also cleared from memory; this was added to abide by NOAA licensing that images would not be persistently stored on the camera.

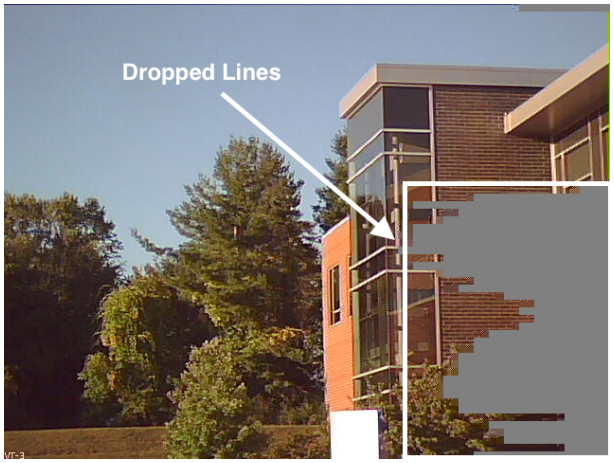

Figure 6: Example Picture With Dropped Lines (Bottom Right)

4.3 Color/Earth Detection

Another feature that was recently integrated into the camera's software was the ability to detect whether or not the camera was taking a picture of Earth. The camera outputs image data with unsigned YUV encoding with a 4:2:2 sampling format; the Y value is the luminance (intensity) component, while U and V values are the chrominance (color) components. In the 4:2:2 sampling format, the U and V components are sampled at half of the rate of the Y component. Effectively, two pixels share the chrominance components, dropping the required memory for an image to 2 bytes per pixel. Since the camera generates YUV encoded data, the easiest algorithm to use for Earth detection was adding a pixelation filter to the image and adding a color detection threshold to determine if the given picture contained enough color to justify it being a picture of Earth.

The color detection algorithm is straightforward, and is executed during JPEG compression to reduce the overhead of the algorithm. Essentially, the image is run through a pixelization filter which averages a block of 8x8 pixels and is similar to downsampling an image (See Figure 7) since the entire block is treated as a single pixel. This occurs during the discrete cosine transform step of the JPEG compression. The average color is then compared to a pre-defined threshold, which determines if the current block contains enough color.

Since the camera generates unsigned YUV data, where the UV components can range from 0 to 255 with (127, 127) representing no-color or grey scale, the color threshold is essentially an 'exclusion zone' to ensure blocks close to grey scale do not pass. In other words, the color value for a specific block of pixels must fall outside of the exclusion zone in order to pass the threshold. Table 3 gives a description of the variables that define the color exclusion zone. Figure 8 shows an example of the UV color scale and Table 5 shows the different operating modes for the camera and each mode's color thresholds (See Section 4.4).

If the total number of blocks that do pass the color threshold exceed an overall percentage threshold, then enough color has been detected in the image and it can be transmitted to the ground.

4.4 Control Commands and Operational Modes

Several new commands have been added to the IHU/Camera UART interface for the ability to control the camera configuration from the ground. These are the '++', 'SS', and 'DD' commands

Table 3: Summary of the Color Threshold Variables

Umax	U component's upper bound for the color exclusion zone
Umin	U component's lower bound for the color exclusion zone
Vmax	V component's upper bound for the color exclusion zone
Vmin	V component's lower bound for the color exclusion zone
Y	Minimum luminance for the Y component
Count	Blocks in the image that must pass the Y, U, V thresholds
Percentage	Percent of blocks that must pass the thresholds

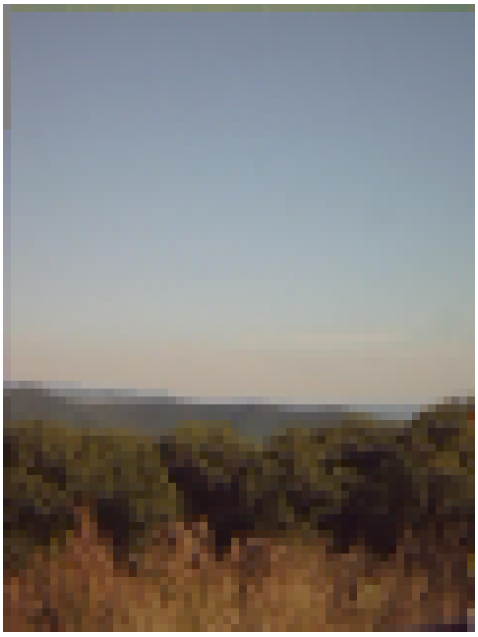

Figure 7: Example of Pixelized Filter Applied to Figure 4

shown in Table 4. The main purpose of these commands is to be able to switch the camera between different operating modes in flight, rather than launching with only a single mode.

The avaliable operating modes are split into two categories: threshold modes (0-5) and picture size (0, 1). Each threshold mode uses a different set of pre-determined values for color and Earth detection, with 0 being the most stringent and 5 being completely disabled. The different threshold modes and the corresponding detection values are shown in Table 5. In order to indicate which mode the camera is currently in, the current number is added to the bottom left corner of the image (See Figure 9).

There are two different resolutions that are supported by the software: either 640x480 (VGA) or 320x240 (QVGA). The primary reason for supporting the QVGA resolution is the ability to store an entire image within the FIFO buffer rather than having to combine two separate images into the final picture. If the satellite is rotating significantly, the smaller images would not have the same discontinuity as the full VGA image.

Each current operating mode is stored in the flash memory chip as two integers, which are then used to generate in-memory structures for the threshold values and image dimensions. During the initial setup after the experiment is enabled, these integers are read from memory and passed to the corresponding populate functions which generates the structures. If the camera detects that

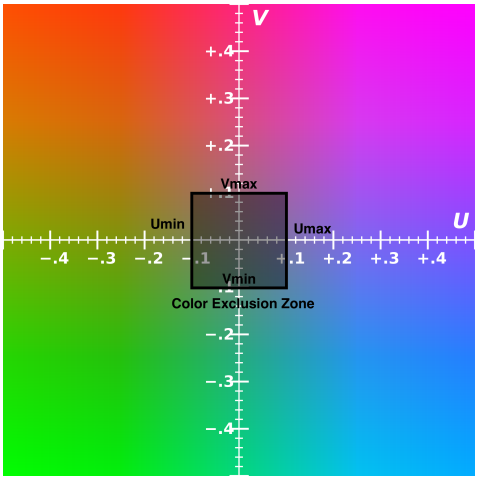

Figure 8: UV Color Scale and Exclusion Thresholds
Note: Unfortunately, since this figure shows the UV color scale, it will not look correct in greyscale.

Figure 9: Indicator for the Camera's Current Mode

the stored mode has been corrupted or is an invalid mode, it will immediately revert to the default mode, populate the threshold and images structures, and save the default mode for the future.

An increment, default, or toggle command can be sent at any time to the camera; however operationally, the IHU only sends the configuration commands to the camera after it has enabled the camera experiment and before it sends *any* other command. When the camera receives the command, it repopulates the corresponding in-memory structure(s) and resets the camera thread, which triggers a new image.

Table 4: IHU/Camera Control Commands

Command	**Response**	**Purpose**
RR	YY/NN/FF	Camera Ready
TT	YY/NN/FF	Transmit Line
++	None	Increment Thresholds
SS	None	Toggle Picture Size
DD	None	Reset To Default

Table 5: Color Detection Thresholds

Mode	**Count**	**Percentage**	$\boldsymbol{Y}$	$\boldsymbol{U}$**max**	$\boldsymbol{U}$**min**	$\boldsymbol{V}$**max**	$\boldsymbol{V}$**min**
0	800	33.33	25	135	119	135	119
1	400	16.67	20	135	119	135	119
2	400	16.67	15	133	122	133	122
3	400	16.67	15	130	125	130	125
4	200	8.33	10	130	125	130	125
5	0	0.00	N/A	N/A	N/A	N/A	N/A

References

[1] OV7670 Linux Driver. URL `http://lxr.free-electrons.com/source/drivers/media/i2c/ov7670.c`.

[2] AL422B Datasheet, 2001. URL `www.frc.ri.cmu.edu/projects/buzzard/mve/HWSpecs-1/Documentation/AL422B\_Data\_Sheets.pdf`.

[3] OV7670 CMOS VGA (640x480) CameraChip with OmniPixel Technology, 2005. URL `www.voti.nl/docs/OV7670.pdf`.

[4] MR25H10 Datasheet, 2015. URL `www.everspin.com/file/208/download`.

[5] STM32L151ZDT6 Datasheet, 2015. URL `www.st.com/web/en/resource/technical/document/datasheet/DM00034689.pdf`.

[6] Proceedings of the AMSAT-NA 31st Space Symposium and Annual Meeting (Houston, Texas). *Virginia Tech Cubesat Camera for FOX-1*. AMSAT-NA, 2013.

GNU Radio Companion Prototype for a Dual Analog/Digital Transponder System for the AMSAT GEO Mission

by
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1 Introduction

The AMSAT GEO mission is a joint effort between AMSAT and the Virginia Tech Ted and Karyn Hume Center for National Security and Technology in order to place an amateur radio payload into orbit. The primary goal of this mission is to enable critical new capabilities to amateur radio operators in emergency response scenarios. More specifically, this amateur radio payload will allow for resilient, and continuous, coverage for amateur radio communications, aid trained operators in mobilizing disaster areas to provide emergency communications support, and support coordination between FEMA and the American Radio Relay League (ARRL).

In order to deploy this amateur radio payload, a rideshare is being established onboard the US Air Force Remote Sensing Program Office Wide Field of View (WFOV) geosynchronous satellite being designed by Millennium Space Systems. The payload itself is a software-defined radio (SDR) payload being developed by Rincon Research Corporation. The list of partners for this mission are: Virginia Tech, AMSAT, ARRL, Millennium Space Systems, US Air Force, and Rincon Research Corporation.

While the AMSAT GEO mission is principally a digital mission, it will be extremely beneficial to have a payload that supports both a digital transponder and a linear bent-pipe analog transponder. This setup will allow for the use of newer technologies through the digital uplink, while also allowing for the use of legacy amateur radio uplinks utilizing traditional analog voice communications. The digital transponder is intended to support up to 100 digital PSK channels using an FDMA based uplink protocol and either a TDMA or CDMA downlink protocol. For the linear bent-pipe transponder, it is

intended to support 90 voice grade channels using single-sideband (SSB) or a single digit number of voice grade channels using narrow-band FM. Given these intended specifications, at present the design of the payload is envisioned to consist of separate linear and digital downlink paths.

The goal of this paper is to provide an alternative to these dedicated downlinks by proposing a dual analog/digital communications system for the payload. More specifically, this work prototypes a communications system in which the linear bent pipe transponder signal is added to the digital transponder signal at a frequency some distance from the main lobe of the digital signal. These signals would then be combined and hard-limited by the payload's final amplifier and transmitted synchronously. At a receiver, a filter can be utilized to recover the intended digital or analog signal with minimal interference from the other signal.

To test this proposed design, GNU Radio was used in order to prototype the transmitted digital BPSK transponder signal, the transmitted AM transponder voice signal, and the AM signal receiver. Analysis of this prototype system demonstrates that the receiver reproduces the voice signal with sufficient fidelity to likely make dedicated digital and analog downlink paths unnecessary.

2 GNU Radio System Prototype

As stated on the GNU Radio project's website, "GNU Radio is a free software development toolkit that provides the signal processing runtime and processing blocks to implement software radios using readily-available, low-cost external RF hardware and commodity processors"[1]. Included in this software development is GNU Radio Companion (GRC), a tool in which GNU Radio signal processing blocks can be connected, reconfigured, and initiated as flowgraphs in a user-friendly graphical interface. In Fig. 1, the GRC flowgraph for the proposed dual analog/digital communications system for the AMSAT GEO mission is presented.

The flowgraph in Fig. 1 consists of three main signal processing chains. At the top of the flowgraph are the signal processing blocks that are used to generate a BPSK modulated signal. This signal represents a prototype for the payload's digital transponder downlink signal. For this work, the data transmitted by this digital signal is chosen to be random (given this paper's focus on the reception of the analog signal).

[1] http://gnuradio.org/redmine/projects/gnuradio

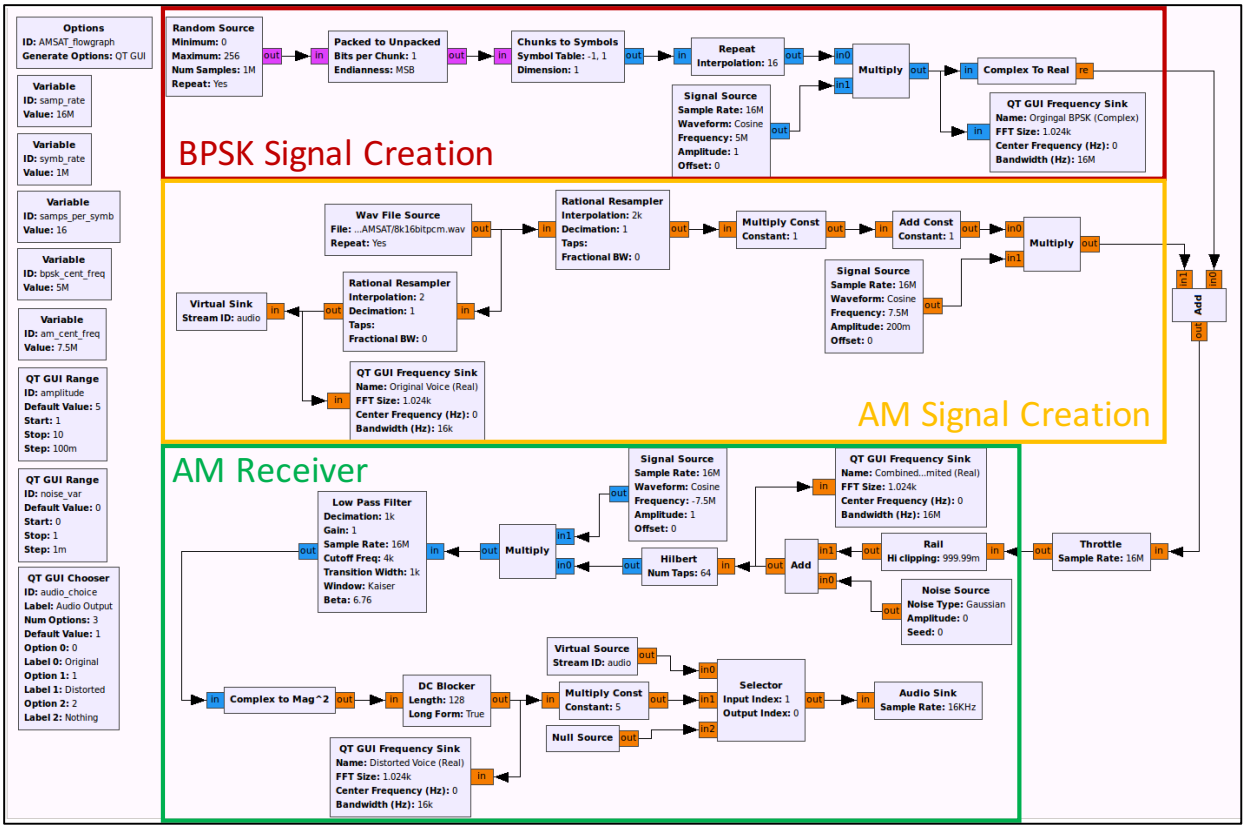

Fig 1: GNU radio companion flowgraph for the proposed dual analog/digital communication system. The digital signal is BPSK modulated and the analog signal is AM modulated. The receiver is designed for the AM modulated signal.

In the middle of this flowgraph are the signal processing blocks that are used to generate an AM modulated signal. This signal is used as a prototype for the payload's linear bent-pipe transponder downlink to be used on the payload for legacy amateur radio voice communications. The data transmitted by this analog signal is a sample voice recording found on the internet[2].

To simulate dual transmission of these signals, the AM modulated signal is up-sampled to the rate of the BPSK modulated signal and frequency shifted to its second side-lobe (which in this case is approximately 20dB down from the primary lobe). The analog and digital signals are then added together and hard-limited to values between -1.0 and 1.0.

Finally, at the bottom of this flowgraph is the AM receiver for the generated dual transmission signal. Here, the signal is first frequency shifted so that the AM modulated signal is at complex-baseband. Next, a low-pass filter is applied in order to largely remove the impact of the BPSK

[2] https://en.wikipedia.org/wiki/WAV

modulated signal. Finally, an AM demodulator is applied to recover the analog voice signal. Note that this process can be replicated with respect to the BPSK modulated signal.

3 Prototype Analysis

The relevant frequency domain outputs for the various signals generated from the GRC flowgraph can be observed in Figs 2 and 3. Given the perfect noiseless channel assumed in Fig. 2, the AM modulated signal can be clearly seen on the second side-lobe of the BPSK modulated signal. As previously stated, this side lobe is approximately 20 dB down from the main side lobe of the BPSK modulated signal. Also note that the frequency representation of the received analog voice signal is largely undistorted when compared against the original transmitted voice signal. For the AWGN channel assumed in Fig. 3, the noise floor has been raised to the level of the BPSK modulated signal's second side lobe. Again note that the received analog voice signal is still clearly discernable above the noise floor and remains largely undistorted. In both cases, the audio signal can clearly be heard above the noise and the content can be clearly heard with minimal distortion.

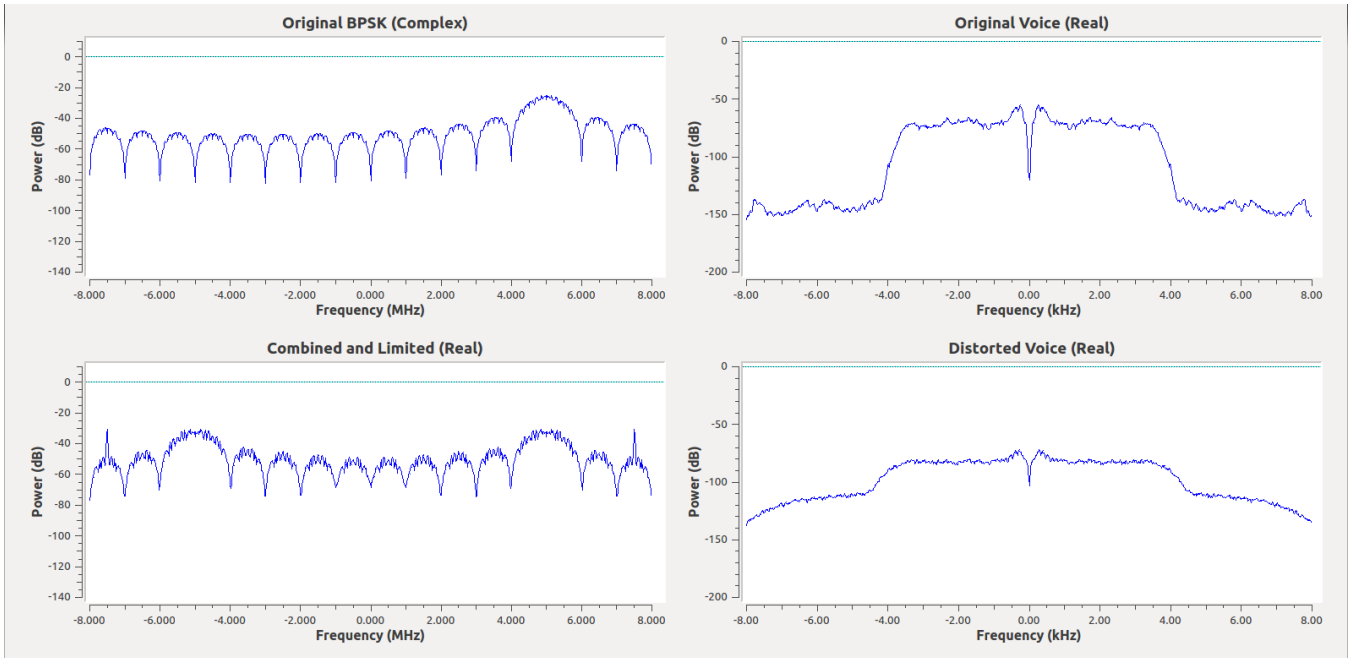

Fig 2: Frequency spectrum of a few of the signals generated from the GNU Radio Companion flowgraph assuming a perfect noiseless channel. Counter-clockwise from top right: analog voice signal before AM modulation, BPSK modulated signal, combined AM and BPSK signals (after hard-limiting), received analog voice signal after AM demodulation.

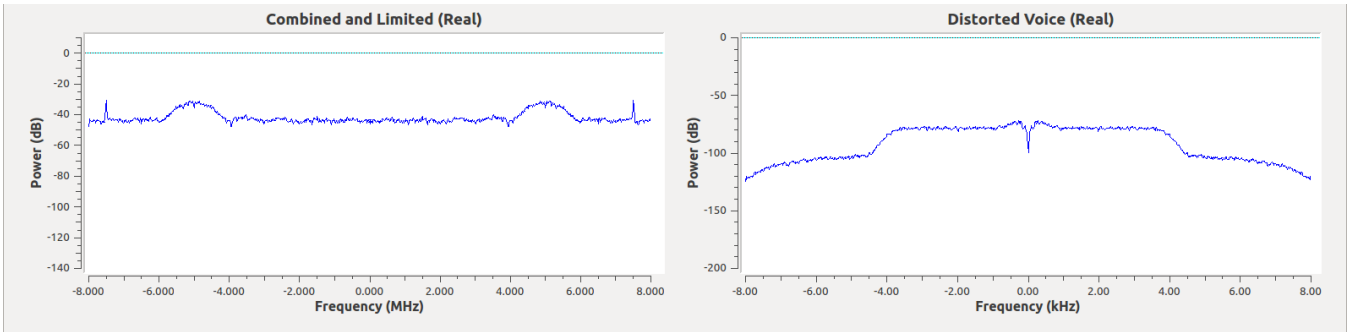

Fig. 3: Frequency spectrum of a few of the signals generated from the GNU Radio Companion flowgraph assuming an AWGN channel. On the left is the combined AM and BPSK signals (after hard-limiting and channel effects) and on the right is the received analog voice signal after AM demodulation.

4 Conclusions

Our results seem to indicate that it will be acceptable, especially at 10 GHz, to simply add the linear bent-pipe transponder signals to the digital modulated waveform on the downlink from the GEO mission payload so long as it is placed well away from the main lobe of the digital signal, even if run through a hard limiting amplifier, as long as the receiver is narrow-band as compared to the digital signal. In other words, the linear bent-pipe transponder can be carried on the same carrier as the digital signal, thus greatly simplifying the communications system on the payload. This is not a "perfect" solution by any means but it could easily have better IMD performance then the Phase 3 HELAPS transponder.

Actor-Based Software Framework for the Virginia Tech Ground Station

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Dr. Robert W. McGwier (N4HY)

1 Introduction

The motivation for creating a ground station at Virginia Tech (VTGS) is to support CubeSats and other communication opportunities with spacecraft in Low Earth Orbit (LEO) at altitudes between 160 km and 2000 km. Most CubeSat projects are concerned with space-based research and providing educational activities for university students. However, there are other uses for a ground station such as radio astronomy and communication with amateur radio satellites. Examples include the reception of Ham TV from the International Space Station or the detection and measurement of galactic hydrogen. Other uses include Telemetry, Tracking, and Command (TT&C) of spacecraft to support future contracts at Virginia Tech. It is important that Virginia Tech be able to handle its own CubeSat missions and allow faculty and students to monitor and communicate with their experiments in orbit, conduct experiments in a course lab, or learn about communications from the vantage point of ground station operations. While there are many ways to construct software for a ground station, certain design choices were made to enable flexible and extensible operations based on the actor model. An extensible signal processing library and module were also developed in this work to enable communications using Software-Defined Radio (SDR).

The VTGS supports many systems: amateur VHF/UHF, amateur L/S-band (1-4 GHz), X-Band (8-12 GHz), and amateur radio astronomy as shown in Figure 1. It is physically located near the Virginia Tech campus on Prices Fork Road in an area away from dense wireless interference. The operations room is located at Space@VT facilities, and networked VPN connections exist between the operations centers and the tracking station. A major goal in the design of the infrastructure for the VTGS was to virtualize as much of the ground station as possible. The software described in this work attempts to do just that by providing a software framework with several components that tackle tasks like scheduling, controls, and signal processing. All of the signal processing should be done in software with baseband samples arriving from the USRP N210 as the last transition in the transmit and receive chain in order to increase the flexibility of this system. This design goal implies the introduction of network infrastructure, which is shown in Figure 2.

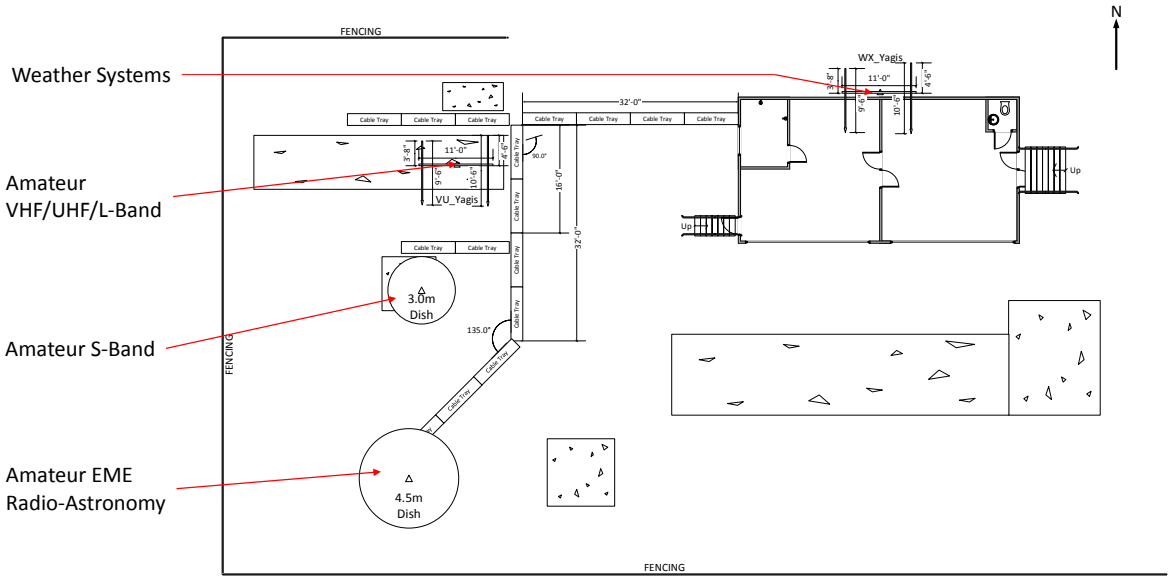

Figure 1: Physical layout and ground plan of the Virginia Tech Ground Station.

2 Pystation Actor Model Framework

The actor model centers around the idea of independent primitives of computation, which communicate only via message passing and share no state. A illustration of actor communication at the VTGS is shown in Figure 3.

Each actor has a mailbox from which it pulls delivered messages in an unspecified order. An actor can also change its behavior in response to a message or create child actors, allowing for dependencies to be created during run time. In order to organize all of the different services across multiple nodes, pystation was created as an actor framework to allow for actor-style programming and to hide many of the issues encountered when designing concurrent and distributed systems across a network. This particular actor framework is based on a small actor implementation by Donovan Preston [1], which motivated the initial use of the Web Server Gateway Interface (WSGI) specification for node-to-node communication. His simple implementation of an actor framework in Python served as an initial example with networking. The incentive for using Python to create the ground station software was due to the dependency on GNU Radio and its ease of use for beginners and new developers. GNU Radio uses Simplified Wrapper and Interface Generator (SWIG) to expose C/C++ signal processing with Python, effectively rendering the scripting language as a glue between blocks. This makes Python a perfect choice for this framework since the intent is to use GNU Radio flow graphs as the physical layer of the VTGS.

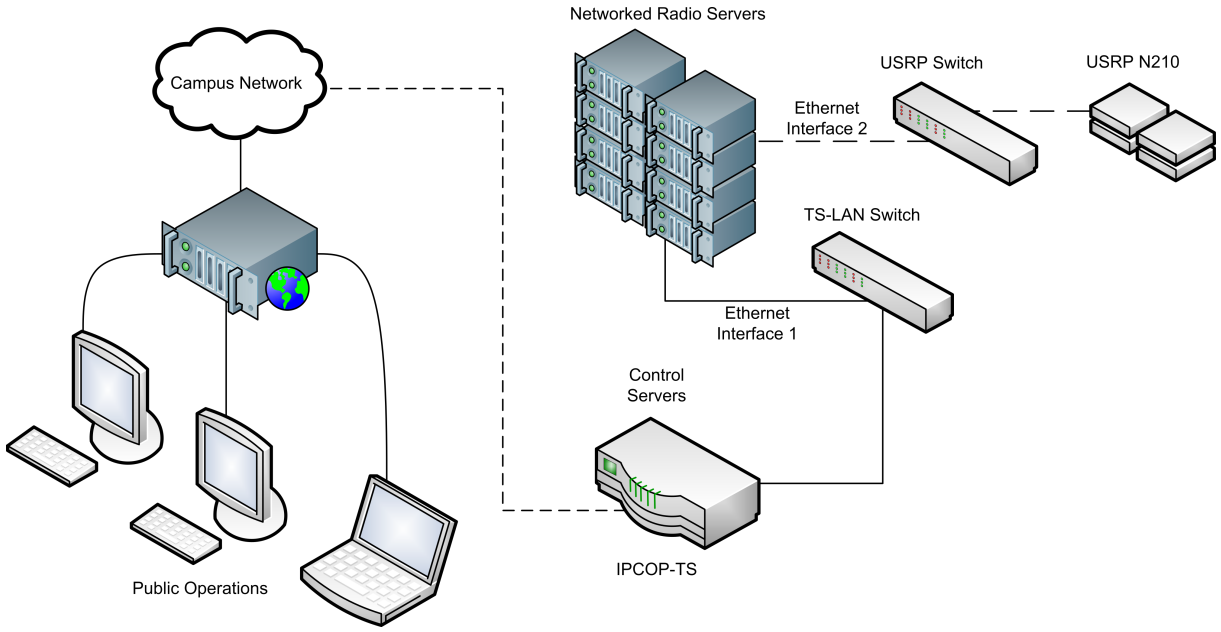

Figure 2: Network configuration of the Virginia Tech Ground Station.

Figure 3: Organization of ground station processes. Messages are delivered to independent mailboxes without sharing memory. Controllers and interfaces manage the message passing between nodes in the network.

3 Expanding to a Peer-to-Peer Network of Ground Stations

In this chapter, a novel P2P protocol is proposed to create a network of ground stations resilient to failure, and capable of communicating with global coverage and scalability. Ultimately, the VTGS is meant to be the start of a larger ground station network.

3.1 Geohashes and the XOR Distance Metric

Some preliminary concepts must be explained before the protocol can be described. In this section, the concept of hashing geographic latitude and longitude coordinates will be introduced, followed by a XOR distance metric for use in that hash space. The hash value or geohash is created from the latitude and longitude of a ground station peer using a geocode system invented by Gustavo Niemeyer [2]. The algorithm for producing a geohash proceeds as follows: Take the latitude value and find whether it falls between -90 and 0 (1) or 0 and +90 (0). For the longitude value, split between the intervals -180 and 0 (1) or 0 and 180 (0). Continue splitting the latitude and longitude coordinate system into smaller and smaller sub-quadrants until the desired accuracy is achieved, adding 2 bits for every set of sub-quadrants. The bits of the latitude and longitude hash values are then interleaved, with latitude as the odd bits and longitude as the even bits.

Each ground station peer has a geohash corresponding to its latitude and longitude coordinates, which are static during the duration of its existence. The geohash of the spacecraft is not static, and changes as its latitude and longitude coordinates change. It is assumed that every ground station

has the ability to fetch updated Two-Line Element (TLE) sets at any time instant from CelesTrak or another source [3] so that each ground station peer is aware of the geohash of a spacecraft. The spacecraft may be rapidly moving in its latitude and longitude, also known as the satellite sub-point, which would induce a small change in its geohash. There are a few special cases, such as moving across the equator, prime meridian, and the poles, which would cause a drastic change in the geohash prefix.

The XOR operation provides a cheap distance metric, as it is easy to compute the XOR value between two binary numbers. It also satisfies the properties of a distance metric in order have some notion of distance, such as coincidence, symmetry, non-negativity, and the triangle inequality:

$$\begin{aligned} \mathbf{XOR}(\mathbf{x}_1, \mathbf{x}_1) &= 0 \\ \mathbf{XOR}(\mathbf{x}_1, \mathbf{x}_2) &= \mathbf{XOR}(\mathbf{x}_2, \mathbf{x}_1) \\ \mathbf{XOR}(\mathbf{x}_1, \mathbf{x}_2) > 0 &\iff \mathbf{x}_1 \neq \mathbf{x}_2 \\ \mathbf{XOR}(\mathbf{x}_1, \mathbf{x}_2) + \mathbf{XOR}(\mathbf{x}_2, \mathbf{x}_3) &\geq \mathbf{XOR}(\mathbf{x}_1, \mathbf{x}_3) \end{aligned}$$

It is important to note that this distance does not correspond to geospatial distance, as the XOR metric is non-Euclidean. However, since two physically close objects tend to have geohashes in the same grid space, their geohash prefixes will be close unless they are edge cases, as shown in Figure 4.

Figure 4: Geohashes are created by adding bits and splitting a grid into quadrants. There are edge cases where hash values differ drastically and the bits are flipped, even though the locations are spatially close.

3.2 Protocol Description

Inspired by advances in P2P technology, such as BitTorrent and its Distributed Hash Table protocol (DHT) [4, 5, 6], the distributed ground stations protocol is based on a DHT where peer identification depends on a geohash value, which is generated based on the latitude and longitude of the ground station. A peer in terms of this protocol corresponds to an entire ground station participating in this network.

Spacecraft also have a latitude and longitude with respect to their TLE set, and so a geohash value can be computed for every instant in time. Using the XOR operation, a distance metric can be computed between geohashes of the spacecraft and ground stations in the network. Control of a spacecraft in the network is determined through a token passing scheme, in which a token representing the spacecraft is passed across the network until it reaches a ground station whose geohash value is "closest" to that of the spacecraft. A token could be a value representing the spacecraft or some kind of unique identifier. This token represents uplink command over the spacecraft to ensure that only one ground station has permission to command the spacecraft at any given time. Thus, only a ground station peer holding this token has the ability to communicate with the spacecraft and send uplink commands. However, this does not preclude multiple ground stations from receiving signals at the same time. This process continues until the token arrives at a ground station in view of the spacecraft. Once a ground station loses contact of a spacecraft, the process continues as described. If the token is lost while in the ownership of a ground station that fails, and the spacecraft arrives

in range of another ground station, a new token will be created given enough time has passed and the Time to Live (TTL) of the token has expired. This idea of a XOR-metric was first utilized in a P2P protocol named Kademlia, and has become the basis for the tracker-less version of BitTorrent [6]. The protocol developed here also benefits from the XOR-metric topology, but combines it with the idea of a token that represents control of the spacecraft. Figure 5 illustrates the idea of passing a spacecraft token around in a network until it reaches a ground station with a geohash "closest" to that of the spacecraft.

Figure 5: Illustration of network discovery. The solid directional lines represent peer discovery while the dotted line represents a token being transferred between peers.

4 Waveform Development for GNU Radio

This section describes some of the waveform development done within GNU Radio and in software. All signal process is performed on servers dedicated to running the pystation framework and GNU Radio.

4.1 Audio Frequency-shift Keying 1200 Baud

AFSK1200 is a digital transmission mode used in amateur radio. It is based on the Bell-202 modem, which is a standard developed by Bell System. The *gr-vtgs* and *planck-dsp* implementations provide a full AFSK1200 modem with transmit and receive capabilities as shown in Figure 6.

Figure 6: The communication flow graph of a Bell-202 style modem. The blocks in blue indicate those developed within *planck-dsp* and contained in *gr-vtgs* for use in GNU Radio.

It employs Frequency-shift Keying (FSK) with a "mark" tone at 1200 Hz, and a "space" tone at 2200 Hz, representing a binary one and zero, respectively. The mode is often used by Automatic Packet Reporting System (APRS), a packet radio system that is responsible for making positioning reports and relaying transmissions between users. A well-written description of APRS, as well as certain ambiguities in its design are available in [7]. AFSK1200 is well within the range of most devices meant to carry audio. Thus, AFSK1200 is typically placed on an FM carrier, adding an outer modulation layer and encapsulating the FSK signal. In addition to the application of inner and outer modulation schemes, data is typically line-encoded as Non-return to Zero Inverted (NRZI). This sort of line-coding can still result in a long run of ones since the transition occurs on a zero, and requires the use of some supplemental run-length limited code.

In order to test the AFSK modem implmentation with USRP, an APRS TinyTrak4 GPS encoder was used to transmit its position [8]. While the conditions were not like that of the channel between a ground station and a spacecraft in LEO, these tests do provide a real world indication of performance. The decoded data displayed a APRS location report with a passing Frame Check Sequence (FCS):

```
/ 2 0 3 0 1 6 h 3 7 1 3 . 8 1 N / 0 8 0 2 6 . 3 5 W > 1 5 5 / 0 0 0 /
T h i s   i s   a   w o r k i n g   T i n y T r a k 4 / A = 0 0 2 1 1 0
```

4.2 Gaussian Minimum-shift Keying or Frequency-shift Keying 9600 Baud

The FSK9600 digital mode, often found in amateur radio circles, is a variation of CPFSK with the addition of a scrambler and the optional addition of a Gaussian filter. In particular, the KD2BD 9600 Baud modem article found in [9] describes a hardware implementation of FSK9600 but does not mention Gaussian filtering in its implementation. Figure 7 illustrates a particular layout of a communications chain with this amateur radio mode.

Figure 7: Implementation of a full FSK 9600 Baud communication chain. Note that the blocks in blue indicate those that were added to GNU Radio through the software packages *planck-dsp* and *gr-vtgs*.

Like in the previous section, an APRS TinyTrak4 GPS encoder was used to test this modem over the air [8]. The Terminal Node Controller (TNC) and hardware radio transmitter and USRP receiver were located in the same room, yielding a high SNR, but it was still much more of a realistic test compared to closed-loop simulations within GNU Radio. A similar location report was decoded with a passing FCS:

```
/ 0 0 0 0 0 0 h 3 7 2 0 . 2 3 N / 0 8 0 4 0 . 6 7 W > 0 0 0 / 0 0 0
V T H A B   T e s t i n g / A = 0 0 6 5 6 3
```

4.3 FUNcube-1 (AO-73) Decoder

A small (10x10x10 cm) CubeSat known as FUNcube-1 (or AO-73), was launched November 21st, 2013 [10]. In order to properly test the VTGS software framework based on contributions of this thesis, it was necessary to use a CubeSat or SmallSat that broadcasts telemetry information over North America. FUNcube-1 met this criteria since one of its major goals was to support the FUNcube Dongle, an SDR receiver meant to allow users to display telemetry information with their software. FUNcube-1 is unique in the sense that it does not support the dominant modems previously discussed in this chapter. In fact, it utilizes differential Binary Phase-shift Keying (BPSK) modulation with some heavy forward error correction, which was originally proposed and written by Phil Karn in [11]. It also has its own custom framing instead of the AX.25 protocol. Figure 8 describes the decoder chain formed in GNU Radio.

Figure 8: Wrapped AO-40 inspired decoder for the FUNcube-1 CubeSat (AO-73). Much of the original forward error correcting code was written by Phil Karn [11]. Note that the blocks in blue indicate functionality that was added in *planck-dsp* and *gr-vtgs*.

To ensure that the decoder works with an actual ground station receiver, some of the older ground station hardware was utilized to record the IQ samples of an actual pass of the FUNcube-1 CubeSat. While most of the data consists of telemetry for the FUNcube-1 dashboard project [12], periodic data about the technical team is also broadcasted as:

```
T h e   m a i n   F U N c u b e   t e c h   t e a m   i s :
D a v e   G 4 D P Z ,   D a v i d   G 0 M R F ,
```

```
D u n c a n  M 6 U C K ,  G e r a r d  A a l b e r s ,
G r a h a m  G 3 V Z V ,  J a s o n  G 7 0 C D ,
J i m  G 3 W G M ,  H o w a r d  G 6 L V B ,
P h i l  M 6 I P X ,  W o u t e r  P A 3 W E G
&  W o u t e r  J a n  P E 4 W J
```

This data was successfully decoded from a live capture at the current location of the VTGS.

4.4 AX.25 Protocol

As part of the development of the basic flow graphs for the VTGS, an AX.25 framer and deframer pair of signal processing blocks were developed for GNU Radio. The framer block reads in a series of bits, packs them into bytes, and calculates the FCS using the CCITT polynomial for the checksum calculation. Prior to transmission, the framer performs an operation known as bit stuffing. In order to avoid a run of ones that would result in the AX.25 flag being misidentified, the standard [13] mandates that a zero be placed after a run of five ones. The deframer simply "unstuffs" the bits by removing a zero after receiving five ones. It is important to note that the receiver must first identify the starting AX.25 flag and wait until it identifies the terminating flag, otherwise the "unstuffing" operation might be accidentally performed on a frame terminating flag.

5 Concluding Remarks

In this paper, we described our software oriented approach to building a flexible and robust ground station at Virginia Tech. This ground station will be capable of joining a larger P2P network of ground stations and serving as an initial peer in that network. We also presented the state of our waveform development within GNU Radio, which serves as the physical layer of our ground station software stack.

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Phase3E Proposed Orbit and Attitude Control Changes

Andrew Rogers, Robert McGwier, Sonya Rowe and Jonathan Black

Introduction and Phase 3 Background

This paper details the orbit and attitude control changes for a proposed collaboration between Virginia Tech (VT) and the Radio Amateur Satellite Corporation (AMSAT). The proposed mission will provide a unique platform to enable real-time, on-orbit application coding and data analysis resulting in an unparalleled on-board radio frequency (RF) processing capability using GnuRadio. The platform will be a satellite in a highly elliptical orbit (HEO) since HEO has desirable properties for ground communication.

The AMSAT Phase 3 satellite relay project was initiated in 1975. Its objective was to develop a series of spacecraft that could provide more reliable communication than previous AMSAT projects [3]. The first three satellites were 150 kg platforms designed and launched between 1980 and 1988. Phase3A, the first satellite, suffered a hull loss when the *Ariane* carrier rocket broke apart during launch [1]. The first Phase 3 satellite to reach orbit was Phase 3B, seen Figure 1, which then carried the designation AO-10 (AMSAT-OSCAR, where OSCAR means Orbital Satellite Carrying Amateur Radio), but was damaged when the upper stage of its carrier rocket collided with it. As a result, it never achieved the desired orbit, however it is still in orbit, but non-functional. Phase 3C (AO-13) successfully reached orbit and worked properly, but reentered at the end of 1996.

Figure 1: Phase 3B satellite

Phase 3D was a much different design; it was a 525 kg vehicle which aimed to continue the Phase 3 line of missions, seen in Figure 2. A rather serious malfunction and subsequent explosion stranded the spacecraft in an equatorial orbit. After a hard reset was commanded by ground

control, the satellite was eventually able to be stabilized using its on board magnetorquers. The satellite operated for four more years until its batteries failed and it deactivated permanently. A

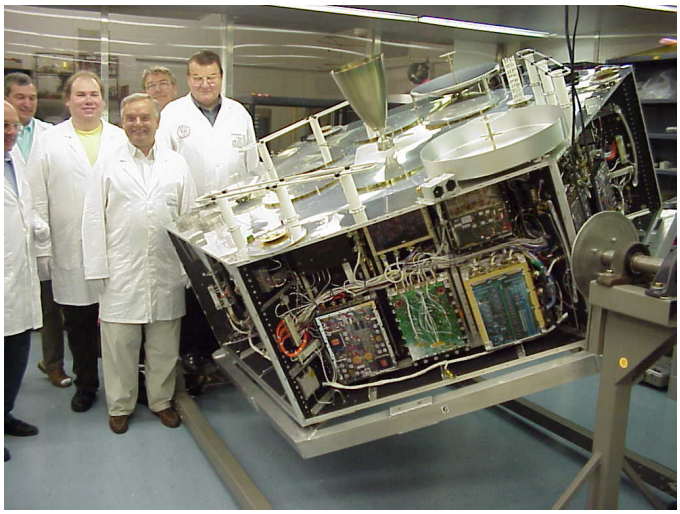

Figure 2: Phase 3D satellite

common feature among the Phase 3 satellites is the desired HEO. Highly elliptical orbits provide hours of continuous visibility per day, and the attitude control can be performed by magnetorquers during periapsis passage. The HEO used by Phase 3 provided up to 12 hours per orbit of northern hemisphere visibility.

Phase 3E (P3E), schematic seen in Figure 3, was initiated in 2004 to continue the Phase 3 series of experiments with the original objectives:

- Provide long range/ long duration communication performance to amateur radio using a high-performance satellite concept based on previous Phase 3 designs
- Test and qualify advanced hardware for Phase 5A and other future AMSAT spacecraft
- Minimal extra qualification by using AO-10,13,40 hardware
- Original launch planned for 2008

The P3E program has been on hold since 2008, and the satellite hardware has been in storage in Germany since then. Virginia Tech plans to complete the development of the P3E spacecraft and oversee its eventual launch.

Orbit Changes

The P3E satellite is to be placed initially into a Molniya-type HEO with an orbital period of 12 hours, and an inclination of $i = 63.4°$, known to be the critical inclination [4]. The critical inclination is the inclination at which the mean effect of the J_2 zonal perturbation on the argument of periapsis, ω, is zero. The rate of change of periapsis due to J_2 is given by

$$\dot{\omega} = \frac{3nR^2J_2}{4a^2(1-e^2)^2}\left(4 - 5\sin^2 i\right)$$

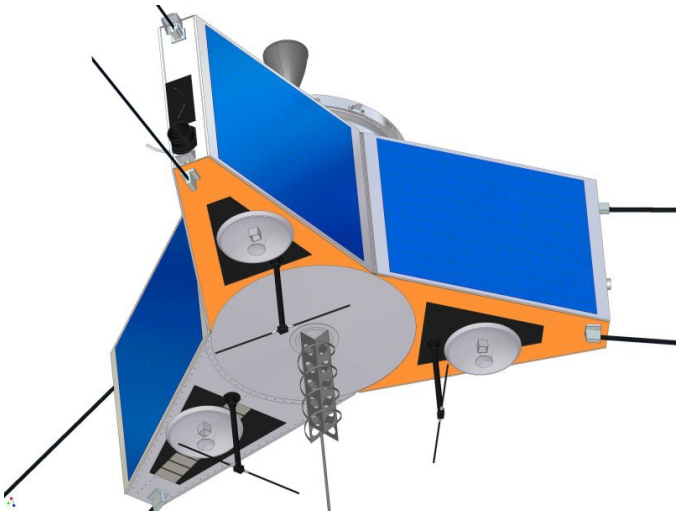

Figure 3: Phase 3E spacecraft schematic

where n is the mean motion of the satellite, R is the radius of the orbit, $J_2 = 1082.6(10^{-6})$, a is the semi-major axis of the orbit and e is the orbital eccentricity. The effect that J_2 has on the periapsis drift is seen in Figure 4.

This inclination is particularly useful for communication satellites because once the orbit is set, the satellite "hangs" at apoapsis for about 11.5 hours. The Soviet Union used networks of three or more Molniya satellites in this orbit to provide continuous coverage of the Northern Hemisphere.

The satellite is also desired to be able to drop down from a 12-hour Molniya orbit to a 6-hour orbit having the same orbital parameters except for the semi-major axis and eccentricity, which would necessarily have to change. The initial and final orbital parameters are given in Table 1.

Table 1: Initial and Final P3E Orbits

Parameter	Initial	Final	Unit
Semi-major Axis, a	236553.4	16815.4	km
Eccentricity, e	0.741	0.591	-
Inclination, i	63.4	63.4	deg
Right Ascension, Ω	141.189	141.189	deg
Argument of Periapsis, ω	270	270	deg
Mean Anomaly, M	0	0	deg

Due to the eccentricity of the orbits, the orbital maneuver must occur at the point at which the initial and final orbits are tangent at periapsis; see Figure 5.

The fuel use required to accomplish maneuvers is measured in Δv. The Δv to perform this 12-hour to 6-hour orbit change is 446 m/s, found using AGI's *Systems Toolkit* (*STK*). This maneuver could be accomplished all at once with an approximately impulsive burn around periapsis. Alternatively, it could be done over several orbits, each at periapsis, which would not lower the total Δv required, but would let a satellite with less thrust accomplish the same maneuver, albeit in a significantly longer period of time. Yet another, but much more advanced option is aerobraking;

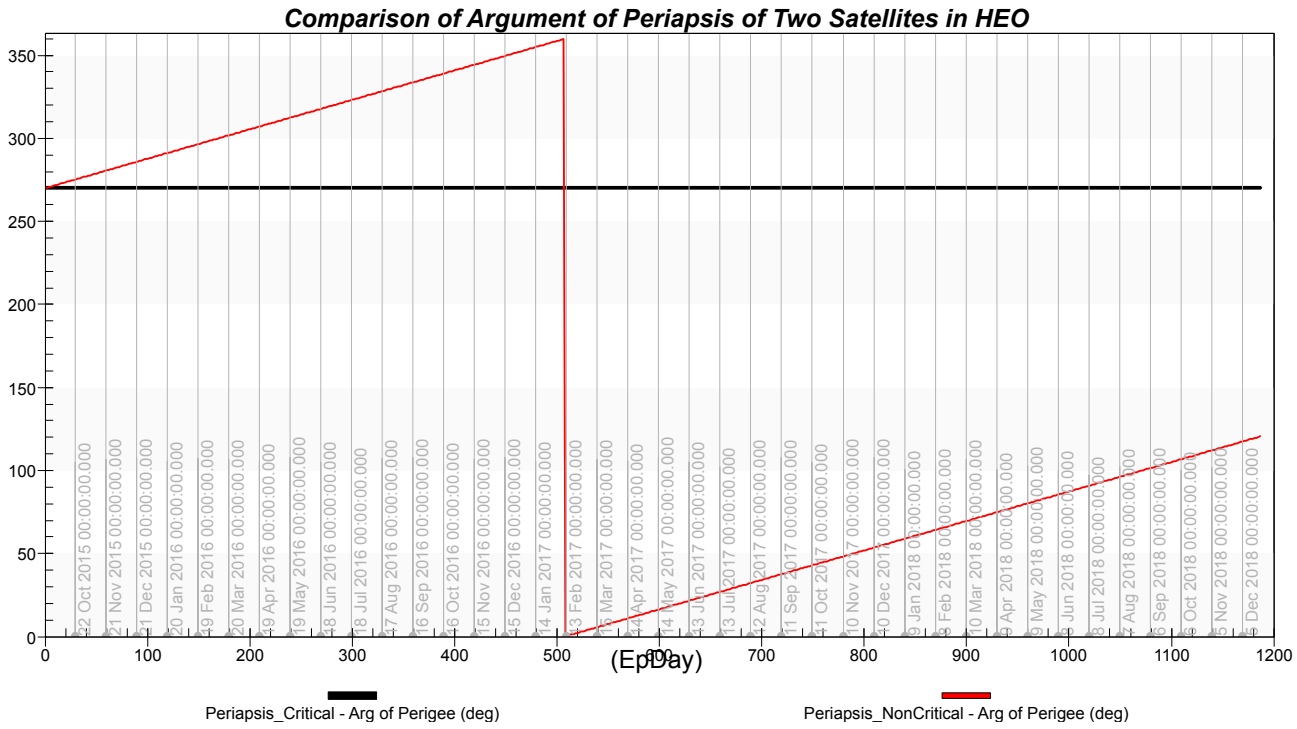

Figure 4: Comparison of a Molniya-type orbit at $i = 63.4°$ and $i = 50°$

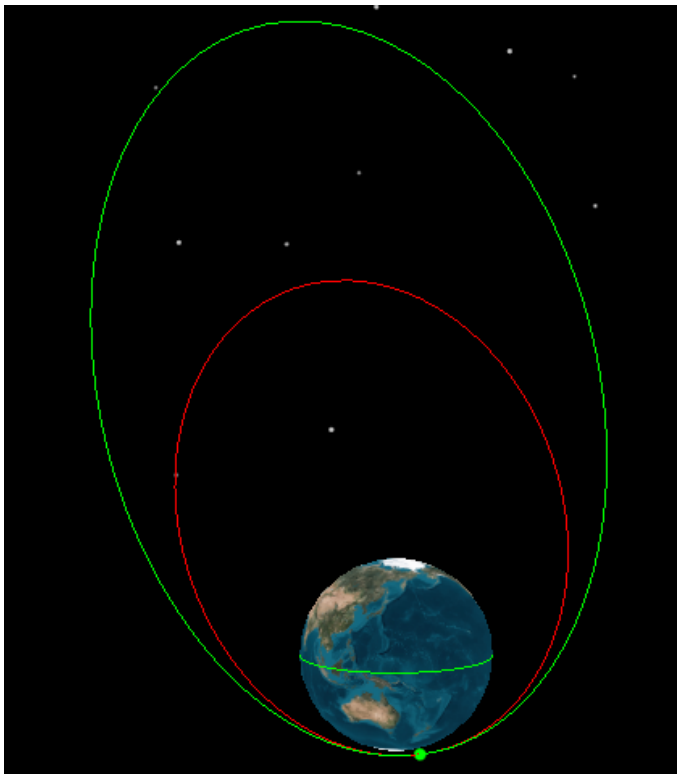

Figure 5: 12-hour orbit (green) and 6-hour orbit (red)

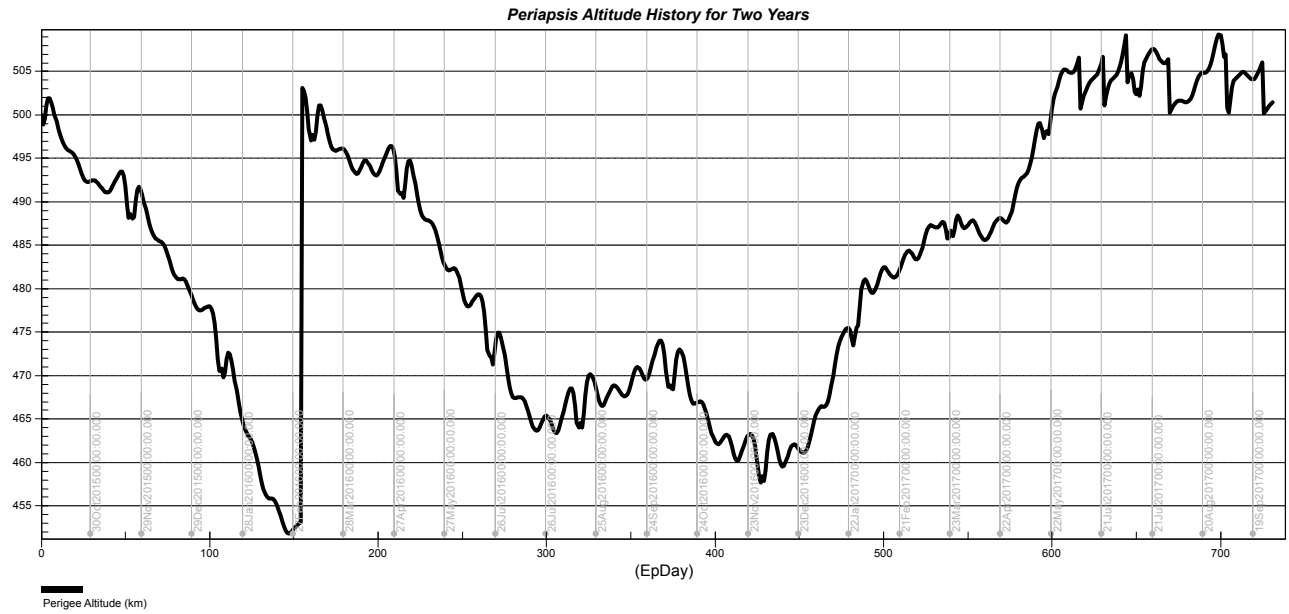

Figure 6: Periapsis altitude over 2 years in orbit

the satellite's passage through the atmosphere could be used over long periods of time to gradually reduce the apoapsis.

Once in the 63.4°-inclined orbit, very little, if any, Δv will be needed to modify the argument of periapsis, since the inclination will be such that the arugment of periapsis will change very little over the foreseeable lifetime of the satellite. The low altitude at periapsis will present some atmospheric drag, and the resulting drop in altitude will need to be corrected. The best time to perform a periapsis altitude correction is at apoapsis where the satellite speed is lowest. For the orbits in this paper, the periapsis altitude is 500 km. In Figure 6, we see that over the span of about 150 days, atmospheric drag will lower the satellite's periapsis by about 50 km. Using *STK*, performing a periapsis correction of 50 km at apoapsis requires 4.3 m/s of Δv. Once the P3E satellite is in the proper orbit, orbital maintenance will not require prohibitively high Δv.

In this analysis, we determined that a total of 15 course corrections would be needed over the two year duration of the simulation. After the major maneuver of $\Delta v = 446$ m/s, the satellite orbits continuously for about 150 days, and in this time the atmospheric drag pulls it into the atmosphere. At a periapsis altitude less than 450 km or greater than 510 km, a sequence that restores the orbit to one with 500 km periapsis altitude and 6 hour orbit period is initiated, the pseudo-code can be seen in Algorithm 1.

The initial effect of the atmosphere on the satellite is that the atmosphere produces enough drag at periapsis (where the satellite's altitude is lowest) that the periapsis altitude lowers. Over longer periods of time, the eccentricity of the orbit gradually decreases and the periapsis altitude raises slightly. This effect can be seen in Figure 6. As the orbit is prevented from decaying into the atmosphere, the secondary effect of the atmosphere becomes most noticeable. The total Δv required for the mission as we have developed it here is 487.6 m/s. Table 2 has the 15 maneuvers, when they occur (in epoch days) and the Δv required.

It should be noted that these maneuvers correspond to just one possible scenario, and the performance of the system could be optimized with more information regarding Δv budget and

Algorithm 1 Orbit Correction Algorithm

if $r_p \leq 450$ km **or** $r_a \geq 510$ km **then**
    Propagate to apoapsis
    Correct periapsis altitude to 500 km
    Propagate to periapsis
    Correct orbit period to 6 hours
else
    Turn engines off
end if

Table 2: P3E Projected Maneuvers

Maneuver	Time, Epoch Day	Δv m/s
1	0.502	446.3
2	154.34	7.76
3	154.46	1.65
4	616.51	23.4
5	616.83	0.556
6	629.77	1.0211
7	629.89	0.1749
8	644.34	0.988
9	644.47	0.305
10	669.46	0.963
11	669.58	0.237
12	701.11	1.8509
13	701.24	0.248
14	725.48	1.986
15	725.60	0.1887

orbital configuration.

Attitude Control Changes

The original P3E command and control system can still be used despite its age, however some modifications will need to be made. The proposed mission reboot involves removal of the original fuel tanks, flow control, ignition electronics and motor, and it involves the addition of added mass due to new payloads and potential ballast weight. As a result, the modified satellite may have substantially different inertial properties.

A popular method of stabilizing satellites for accurate pointing is through spin stabilization. The satellite is spun about its major axis and behaves as a gyroscope. For the P3E spacecraft, the major spin axis is the $\pm Z$ axis. Spinning around this axis results in stable attitude orientation. In the absence of disturbance torques, spin stabilization will maintain a fixed attitude in inertial space. In reality, numerous disturbances will be present, so reaction wheels will be added. The reaction wheels serve two purposes. At apoapsis, they will serve as the primary nadir-alignment mechanism, which is necessary to provide good communication links. In addition to nadir alignment, reaction wheels also absorb the angular impulse of the myriad environmental disturbances [2].

In order to prevent the reaction wheels from saturating and thus be unable to absorb this angular impulse, some mechanism for dumping excess angular momentum must be used. A common approach is to use magnetorquers; the P3E spacecraft already has magnetorquers in its design, so this is a natural choice. The magnetorquers will help dump excess angular momentum from the reaction wheels, as well as use the Earth's magnetic field to align the $\pm Z$ axis with nadir when the satellite is around periapsis.

The development of the new control system for the P3E satellite will be a challenging and fascinating process. There will be a rich body of work when determining the layout of the attitude control system. The primary mode of operation will be maintaining the $\pm Z$ axis of the satellite with the nadir vector (which points at the Earth). The combination of the magnetorquing system with small reaction wheels will provide Virginia Tech with a challenging control design problem, and successful deployment will ensure that the satellite is of maximum utility to the AMSAT community.

Summary

In this paper, the proposed collaboration between AMSAT and Virginia Tech has been discussed. Relevant background on the Phase 3 AMSAT program was presented. An orbital analysis regarding the Δv required to maneuver from a 12-hour Molniya orbit to a 6-hour orbit was also presented. For a sample mission profile of P3E, less than 500 m/s Δv were required to maintain the satellite in a 6 hour orbit over 2 years. Finally, aspects of the attitude control for the satellite were discussed.

Acknowledgments

We would like to thank John Klingelhoeffer, Michael Parker, Thomas Clark and Gerald Buxton for their support in this project.

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Mitigating Earth-To-Space Propagation Effects through Adaptive Waveform Switching

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1 Introduction

The Hume Center at Virginia Tech is working in collaboration with the Space Communications and Navigation (SCaN) Testbed team at NASA Glenn Research Center in order to enhance their communication capabilities in the unique Earth-to-Space propagation environment. In this work, first a research study is presented on the types of propagation effects that typically impact these channels (such as path-loss, Doppler, shadowing, etc.) and from this study a simulation model for these channels is developed using both MATLAB and STK. Based on the developed model, an adaptive waveform switching algorithm is then proposed in order to mitigate these propagation effects. On-orbit algorithm performance evaluation is planned using the SCaN Testbed on-board the International Space Station.

2 Link Configuration

This work outlines the research groundwork that will culminate in eventual flight experiementation on the SCaN Testbed. The SCaN Testbed has several software defined radios (SDRs) installed on the International Space Station (ISS) which are open for the research community's use in experiments. The following analysis is performed with the flight SDR in mind.

Figure 1 depicts the link configuration that is considered for this research analysis. In this model, only the Earth-to-Space uplink will be considered and analyzed for a link adaptation algorithm. The ground station transmitting to the SDR on-board the ISS will be located at the NASA Glenn Research Center (GRC) in Cleveland, Ohio. The transmitter will be designed in GNURadio with the ability to switch between modulation schemes. At the receiver onboard the ISS, decision logic will determine if the received signal energy will maintain the desired bit error rate (BER). If the BER increases beyond the threshold, the receiver will decide that a different modulation scheme needs to be transmitted. For instance, if the SDR is receiving a 16-QAM signal but the signal power degrades, the decision algorithm may decide that a QPSK signal will provide more fidelity. The current desired modulation scheme will be conveyed to the ground station transmitter via the downlink. The downlink will be a BPSK control channel, with high fidelity and no modulation adaptation capabilities. While the transmitter transitions to a different modulation scheme, the receiver will wait such that no data is lost.

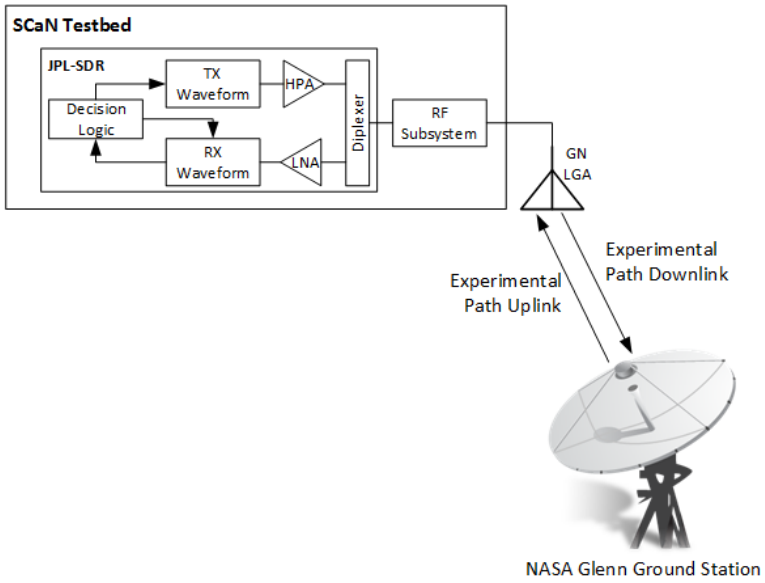

Figure 1: NASA SCAN Testbed on-board the ISS

2.1 Ground Station Specifications

In the following propagation model, the uplink will be used in the development and analysis. Table 1 depicts the parameters of the GRC ground station that will serve as the uplink transmitter.

Table 1: GRC Ground Station Specification

S-band Frequency	2.07 GHz
Transmitter Power	10 W
Data Rate	155.346 kSps
Antenna Diameter	2.4 m

2.1.1 Ground Station Gain Calculation

The transmitting antenna gain is used in the propagation modeling in Section 3. The calculation of the ground station transmitting antenna uses Equation 1. The values of diameter and wavelength are calculated from values in Table 1. The value for efficiency is approximated as a commonly accepted efficiency for a parabolic antenna

$$G_{TX} = \eta \left(\frac{d\pi}{\lambda} \right)^2 \tag{1}$$

η, efficiency	0.65
d, diameter	2.4 m
λ, wavelength	0.14 m
Tx Antenna Gain	**32.5 dB**

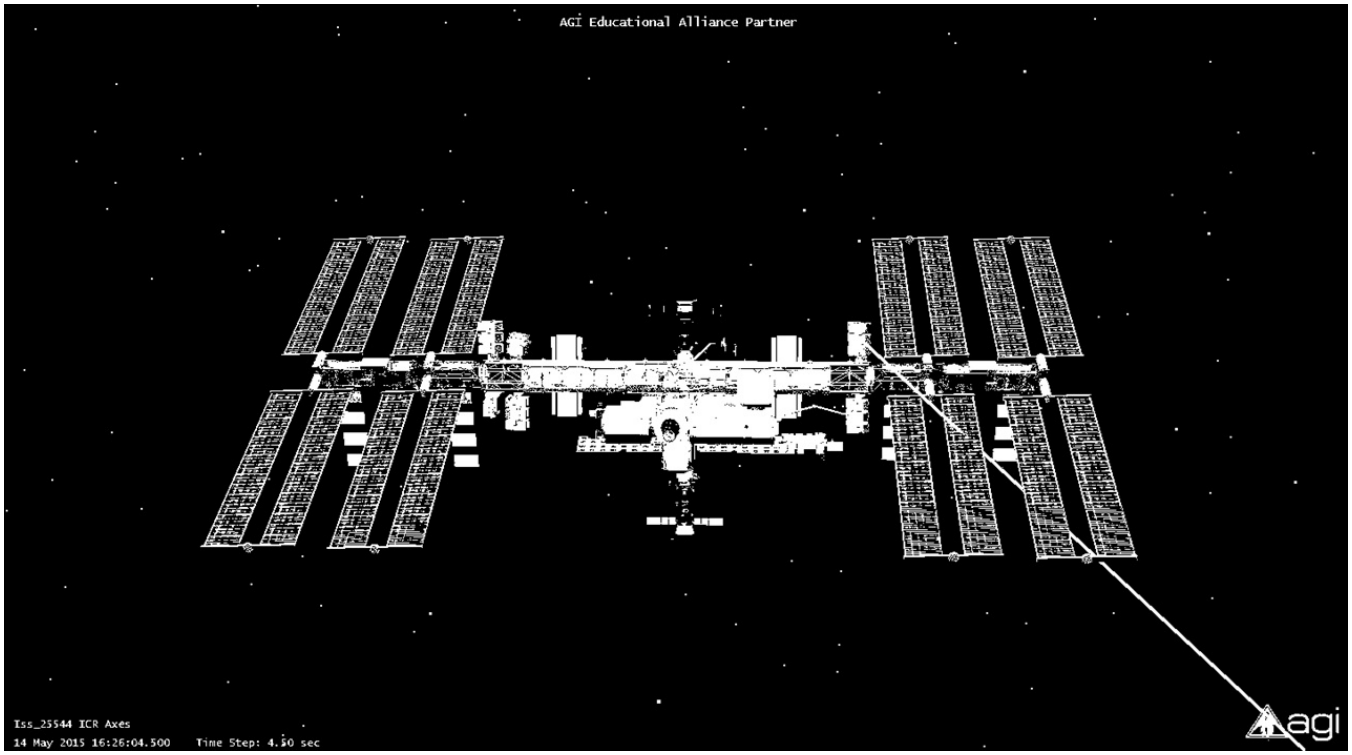

Figure 2: NASA SCAN Testbed on-board the ISS with Solar Panel Obstruction

3 Propagation Analysis

In Earth-to-Space communications, links experience degradation on the path from the ground station to the receiver. This degradation can be caused by effects such as: path loss, atmospheric losses, and shadowing. Shadowing can occur when the receiving antenna is partially blocked by obstructions such as the satellite body or solar panels. In the case of the SCaN Testbed, due to its location on the ISS, it can experience obstruction by the body of the ISS or its solar panels, as seen in Figure 2 during certain passes. This obstruction greatly reduces the strength of the link and can limit communication capabilities.

3.1 Systems Toolkit

This analysis utilizes the Analytical Graphics, Inc. (AGI) Systems Toolkit (STK) software for modeling this paper's scenario. Visuals of the STK interface are seen in Figures 3 and 4. STK also has a MATLAB interface capability, which enables users to instantiate satellites, ground stations, receivers, antennas, etc. and then perform analysis on these objects from MATLAB. The STK/MATLAB interface was used to set up the ISS, GRC ground station, ISS SDR receiver, and SDR antenna. The STK scenario then calculated accesses, or times during which the satellite is visible to the ground station. STK also provides values for range and range rate, both of which are used in this project for propagation modeling. The longterm vision of the STK/MATLAB interface for this model is to develop a real-time script that calculates the link's health and then adapts the waveforms accordingly on the receiver.

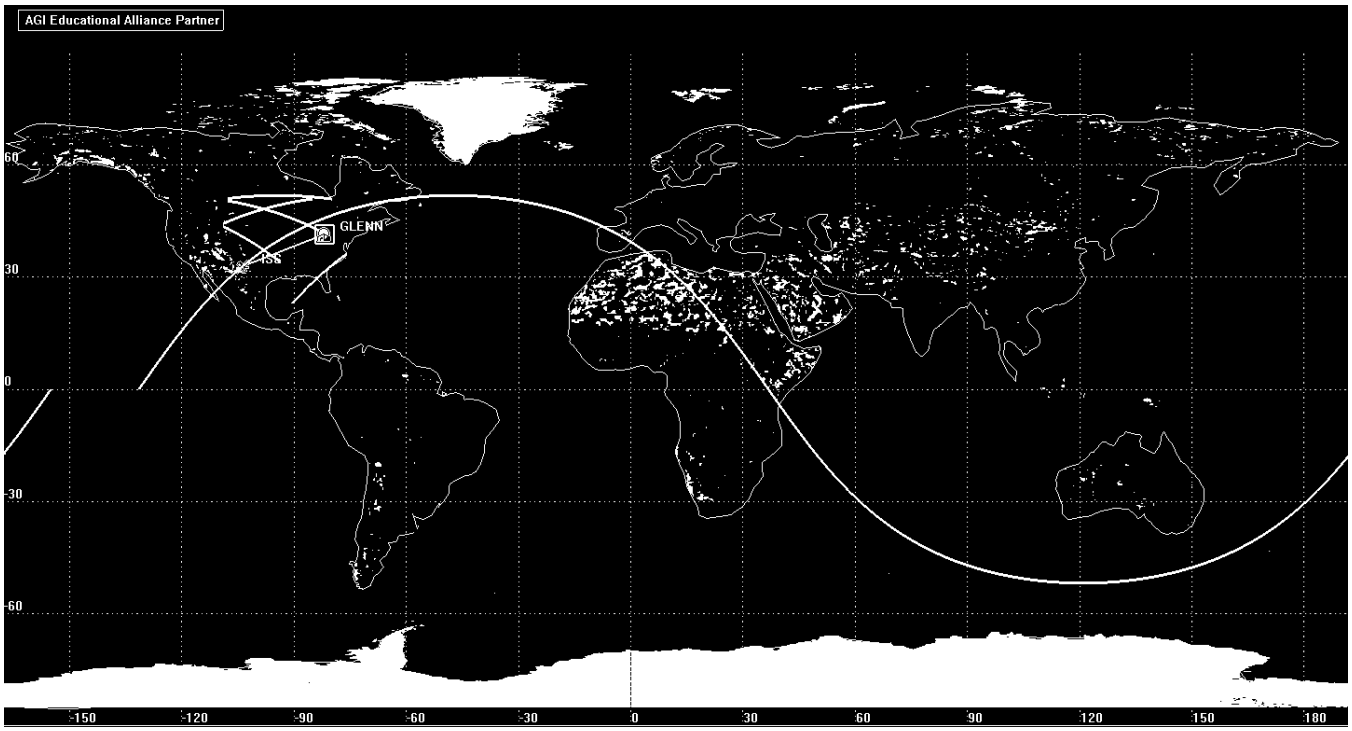

Figure 3: ISS orbit ground track with accesses to Glenn Research Center

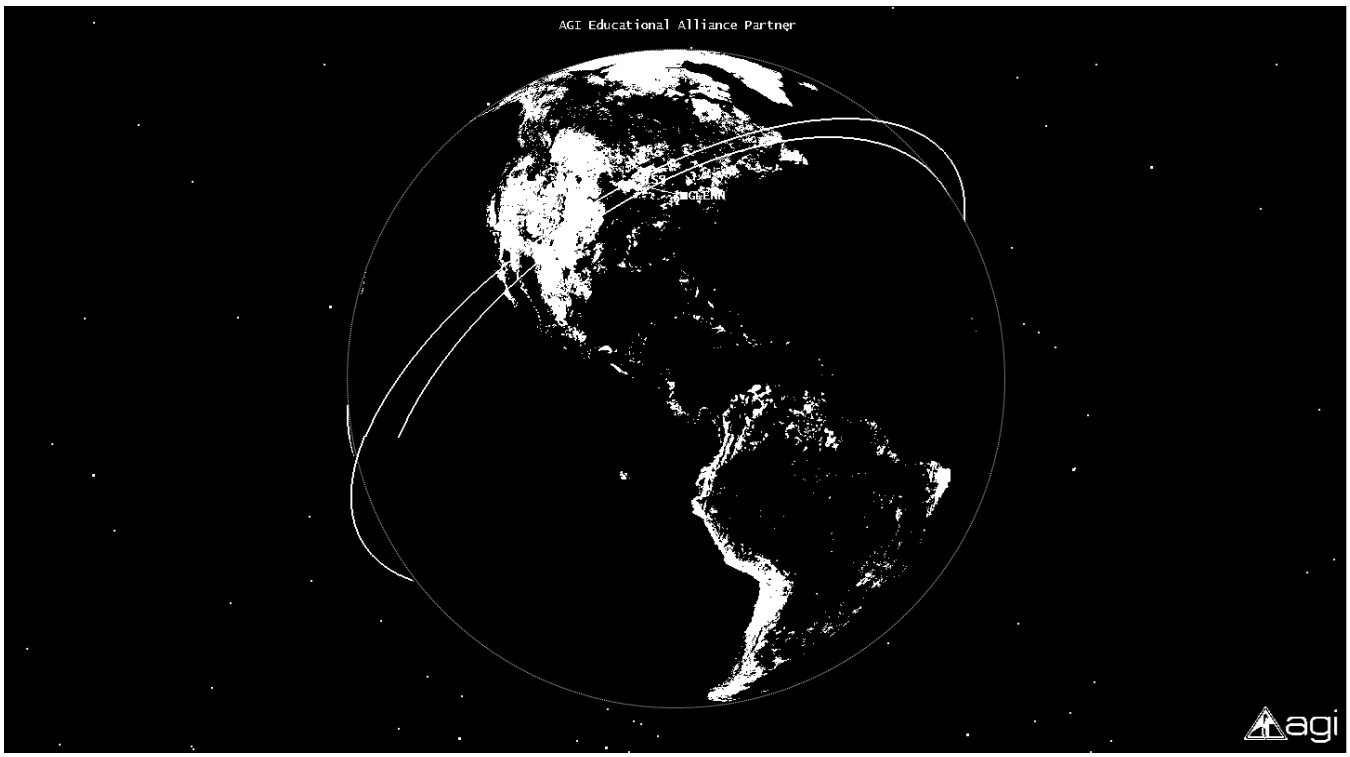

Figure 4: ISS global orbit track over the GRC

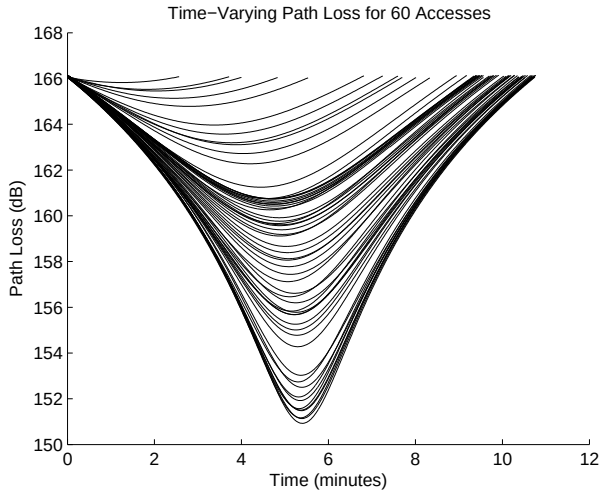

Figure 5: Path Loss for 60 Accesses

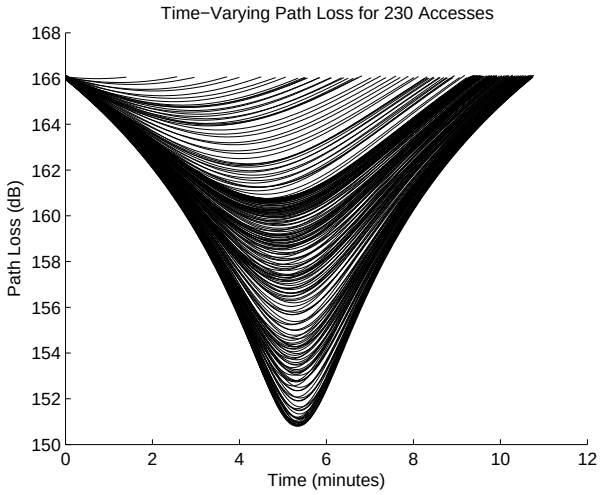

Figure 6: Path Loss for 230 Accesses

3.2 Path Loss

Path loss is an important consideration in a communications link budget as it introduces considerable loss and varies across each satellite pass. With each access having a different path loss curve, a wide range of values for path loss are experienced by the radio on-board the ISS. Additionally, an important consideration with path loss during a pass is that it continuously changes with time, so monitoring must be continuous.

In the analysis for this project, range data from an STK simulation was used to estimate the range value used in calculating path loss. Figure 5 displays how the path loss changes over time for 60 out of the 230 accesses occuring during the month period April 21, 2015 to May 21, 2015. Figure 6. As can be seen from both Figures 5 and 6, some passes have very low path loss at certain times, while other passes have a much higher path loss value. The time-variant path loss will be constantly monitored in the receiver link-budget analysis to determine if a waveform-switch is necessary.

For this work's link budget, the STK range statistics report identified the maximum and minimum ranges for a one-month scenario period from April 21, 2015 to May 21, 2015. Both the maximum and minimum path losses were calculated using the free-space path loss equation, Equation 2, with a free-space exponent value of $n = 2$. Using maximum and minimum range values from an STK analysis over the month period, the maximum and minimum path losses to be expected are seen in Table 2.

$$L_P = 10 \log_{10} \left(\frac{4d\pi}{\lambda} \right)^n \tag{2}$$

Table 2: Maximum and Minimum Path Loss Calculations

Minimum		**Maximum**	
d, range	369.9 km	d, range	2328.7 km
λ, wavelength	0.14 m	λ, wavelength	0.14 m
n, path loss exponent	2	n, path loss exponent	2
Path Loss, L_P	**150.7 dB**	**Path Loss**, L_P	**166.1 dB**

For the overall link budget analysis, the maximum path loss value is used to determine the low bound on the carrier-to-noise ratio experienced by the flight SDR.

4 Link Budget

The link budget calculation incorporates many the values considered in previous sections and returns the carrier-to-noise ratio (C/N). This C/N value will be used in the adaptive waveform decisions as it relates to the bit-error-rate calculations.

4.1 Equivalent Isotropically Radiated Power

First, when calculating the link budget analysis, the Equivalent Isotropically Radiated Power (EIRP) is calculated for the transmitter using Equation 3. The value for the transmitter loss is estimated, similarly to the noise figure and antenna temperature in Section 4.3.

$$\text{EIRP}_{TX} = P_{TX} + G_{TX} - L_{TX} \tag{3}$$

Table 3 details the values for each of the variables in Equation 3.

Table 3: EIRP Calculation Summary

P_{TX}, Transmitter Power	10 W
G_{TX}, Transmitter Antenna Gain	32.5 dB
L_{TX}, Transmitter Loss	2 dB
EIRP$_{TX}$	**40.5 dBW**

4.2 Received Power

The next step after determining the EIRP is to calculate the received power. When calculating the received power, Equation 4 is used.

$$P_{RX} = \text{EIRP}_{TX} - L_P - L_{atmo} - L_{iono} + G_{RX} \tag{4}$$

The terms for Equation 4 are defined in Table 4.

Table 4: Equation 4 Variable Definitions

EIRP$_{TX}$	Effective Isotropically Radiated Power
L_P	Path Loss
L_{atmo}	Atmospheric Losses
L_{iono}	Ionospheric Losses
G_{RX}	Receiver Antenna Gain

Table 5 shows the summary of values and returns the received power value of -123.7 dBW. The atmospheric losses, ionospheric losses, and receiver antenna gain are all estimated values in this calculation. In final link budget analysis, more accurate values will be used. Additionally, the maximum power loss calculated in Section 3.2 is used to model the worst-case scenario.

Table 5: Received Power Calculation Summary

EIRP_{TX}	40.5 dBW
L_P	166.1 dB
L_{atmo}	1 dB
L_{iono}	1 dB
G_{RX}	4 dB
P_{RX}	**-123.7 dBW**

4.3 System Temperature

For the purposes of this initial link budget analysis, the noise figure is an estimated 5 dB and the antenna temperature is estimated at 200 K. The reference temperature is assumed to be the standard 290 K. These estimated values are used to calculate the system noise temperature; however, eventually parameters for the flight SDR will be used to ensure high accuracy of the link budget.

$$T_{ref} = 290 \text{ K}$$
$$\text{NF}_{dB} \approx 5 \text{ dB}$$
$$T_{ant} \approx 200 \text{ K}$$

Using the estimated values, the noise temperature of the receiver can be calculated using Equation 5.

$$T_{RX} = T_{ref}\left(10^{\frac{\text{NF}_{dB}}{10}} - 1\right) \tag{5}$$

Therefore, $T_{RX} = 432.5$ Kelvin.

From the receiver noise temperature, the system temperature can then be calculated using Equation 6 and Table 6 summarizes the values used in the calculation.

$$T_{sys} = T_{ant} + T_{RX} \tag{6}$$

Table 6: System Noise Temperature Summary

T_{ant}, Antenna Temperature	200.0 K
T_{RX}, Receiver Temperature	432.5 K
System Temperature	**632.5 K**

4.4 Carrier-to-Noise Ratio

With the received power, the carrier-to-noise ratio can be calculated using Equation 7.

$$C/N = P_{RX} - P_n \tag{7}$$

Noise power, P_n, is defined in Equation 8. The parameters used in this equation are listed in Table 7.

$$P_n(dB) = k + T_{sys} + B_n \tag{8}$$

Table 7: Equation 8 Variable Definitions

k, Boltzmann's Constant	1.39×10^{-23} J/K
T_{sys}, System Temperature	632.5 K
B_n, Noise Bandwidth	155.346 kHz

Table 8: Carrier to Noise Ratio Calculation

P_{RX}	-123.7 dBW
k	-228.6 dBW/(dBK/Hz)
T_{sys}	28 dBK
B_n	59 dBHz
C/N	**25 dB**

Therefore, the worst-case C/N at the receiver is 25 dB.

4.4.1 E_s/N_0

In order to perform analysis on bit error rates for varying modulation schemes, the carrier-to-noise ratio needs to be related to the received energy per symbol. The equation for that is as follows:

$$\frac{E_s}{N_0} = \frac{C}{N}\frac{B}{R_s} \tag{9}$$

The symbol rate is 155.346 kSps on the flight SDR and 6 MHz was assumed as the bandwidth. Therefore, E_s/N_0, at the worst path loss without any shadowing, is 30.9 dB.

4.5 Shadowing

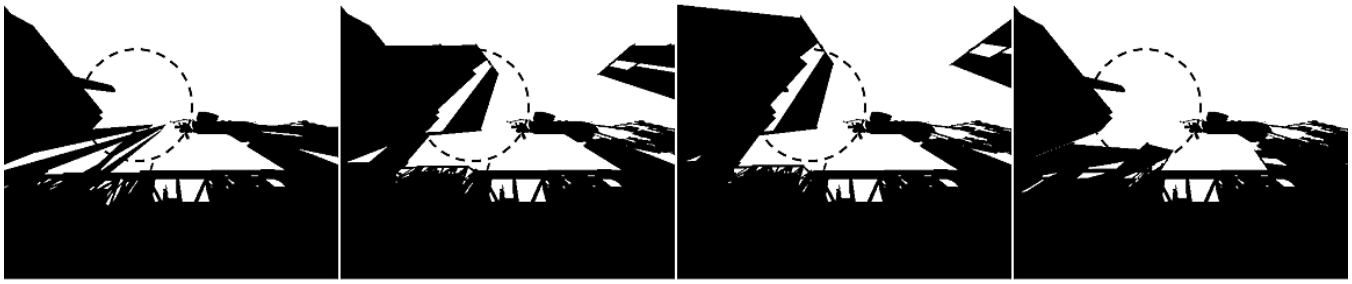

Figure 7: Obscuration Tool

Determining the best model for shadowing experienced by the receiver is still in the early stages. A research study performed by NASA found that the antenna pattern decreases by about 6 dB when a solar panel obstructs the antenna [1]. In STK, a metric or check will need to be defined in order to determine when the receiver is undergoing obstruction. The obscuration tool seen in Figure 7 can calculate the percent of obstructed area looking down the antenna's boresight. Using this tool, the model can trigger when shadowing is occuring and consider the additional loss incurred by shadowing–a value approximately 6 dB.

5 Doppler Shift

Doppler shift is another time-varying parameter that needs to be addressed in the uplink. Because Doppler shift can be calculated before a link is established with the satellite, the ground station transmitter will adjust for the shift as communication begins. The Doppler shift will be calculated before the pass begins using data from STK.

STK returns range rate for each time step in the satellites pass, so Doppler shift can be calculated using Equation 10 with the parameters defined in Table 9. Because the transmitter on the ground will be adjusting for the Doppler shift, instead of the receiver, the Doppler graph for analysis will be inverted from the typical Doppler graph.

$$f = \left(\frac{c}{c + v_r}\right) f_0 \tag{10}$$

Table 9: Doppler Shift Equation 10 Variable Definitions

c , velocity of waves in free space	3×10^8 m/sec
v_r, velocity of receiver relative to source	range rate from STK
f_0, emitted frequency	2.07 GHz

The observed maximum and minimum range rates for the ISS from STK are in Table 10, as well as the calculated, expected shifts at a range of +/- 50 kHz.

Table 10: Minimum and Maximum Doppler Values

Range Rate Maximum	+6.8 km/sec	+50 kHz
Range Rate Minimum	-6.8 km/sec	-50 kHz

In Figure 8 and 9, the Doppler shift is plotted across time for 60 and 230 accesses, respectively. Similar to the path loss, different passes have varying Doppler curves. Each individual curve is almost symmetric across zero, which indicates that the ISS orbit is near-circular. The transmitter will calculate the expected Doppler effect for the pass and then adapt for it as the pass occurs.

6 Decision Bounds

6.1 Bit Error Rate Curves

The BER of the received data stream will be the measure of performance and the determining factor for when the receiver should switch modulation schemes. Figure 10 plots the bit error rate against E_s/N_0 for each modulation scheme. The standard E_b/N_0 vs. BER plot seen in digital communications does not demonstrate the required increase in power for QPSK from BPSK, so the E_s/N_0 axis allows for the comparison between all considered modulation schemes. Table 11 lists the BER equations for the curves in Figure 10 with E_s/N_0 rather than an E_b/N_0 parameter.

6.2 Block Coding

Coding is also a future consideration that will be implemented in the transmitter and receiver. It gives additional gain in these curves, and is thus an added benefit. The specific coding protocol to

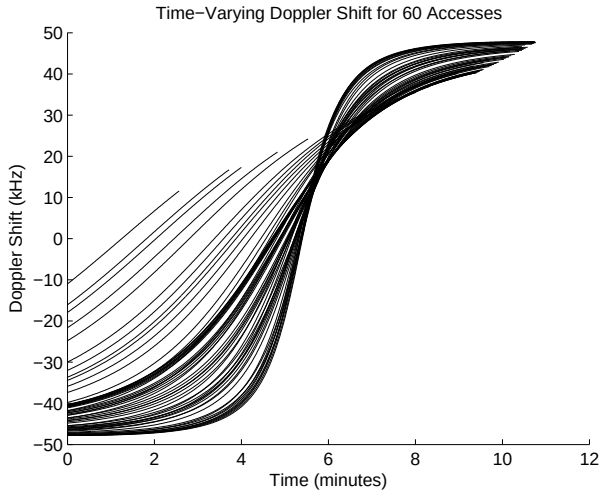

Figure 8: Doppler for 60 Accesses

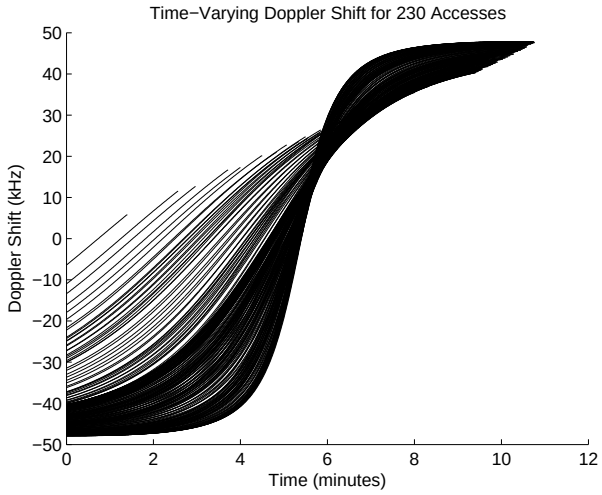

Figure 9: Doppler for 230 Accesses

Table 11: Bit Error Rate Curves

BPSK	$P_b = Q\left(\sqrt{\frac{2E_s}{N_0}}\right)$
MPSK	$P_b = \frac{2}{\log_2 M} Q\left(\sqrt{\left(\sin\frac{\pi}{M}\right)^2 \frac{E_s}{N_0}}\right)$
MQAM	$P_b = \frac{4}{\log_2 M}\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3}{M-1}\frac{E_s}{N_0}}\right)$

be used will be investigated and then implemented before the on-orbit experimentation. However, no adaptive coding will occur–instead all modulation schemes will have the same coding scheme.

6.3 Acceptable BER Threshold

Once a complete propagation model is developed, the waveform switching algorithm will be the next step in the experiments completion. One primary consideration in the algorithm will be the acceptable BER threshold. The value will need to be low enough that errors are not rampant in the received data, but high enough that different modulation schemes can achieve it depending on the received E_s/N_0. For the purposes of the following plot, the BER threshold was selected as 10^{-4}, which is 1 in 10,000 errors. As can be seen in Figure 11, at a BER threshold of 10^{-4}, the receiver switches between modulation schemes at approximately every 5 dB increase in E_s/N_0. With increasingE_s/N_0, the receiver switches to a higher modulation scheme and increases data rate; at decreasing E_s/N_0, the modulation schemes transition lower with a lower data rate.

Another important concern for the development of this algorithm is the design of thresholds that remove any hysteresis of the decision bounds. The receiver should not be switching between the modulation schemes when there is slight variation right on the border in the decision threshold. This would be counterproductive as every transition from modulation schemes causes a delay in transmission. As this project approaches the next stage, designing thresholds such that the receiver has only smooth transitions will be critical.

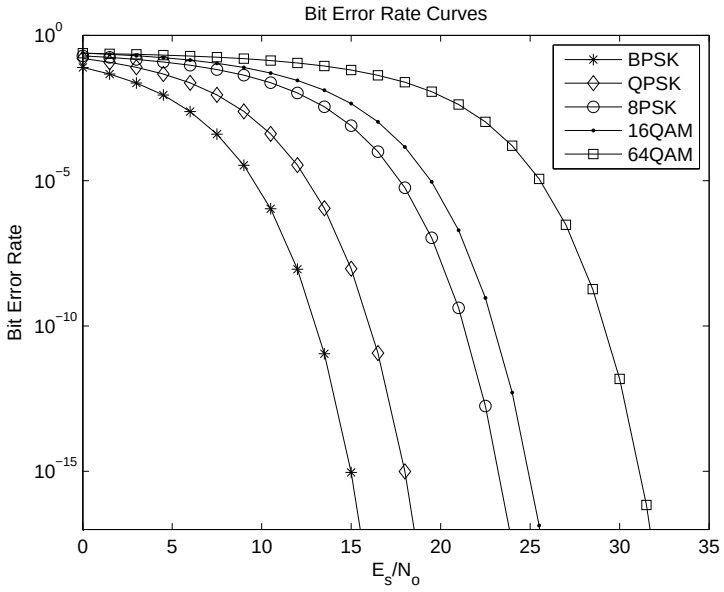

Figure 10: Bit Error Rate Curves for Analyzed Modulation Schemes

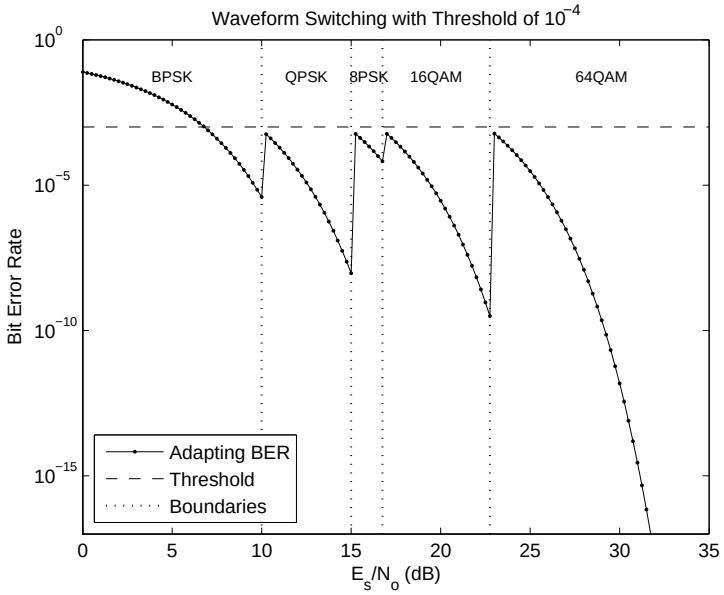

Figure 11: Simulated Switching at a BER Threshold of 10^{-4}

7 Conclusion

This project leads the way to more future work on this collaborative NASA research effort. After finalizing a propagation model, the waveform switching algorithm will be developed and simulated. The propagation model itself has several more stages to go until it reaches completion. The shadowing model will require additional literature reviews and some experimental analysis to determine the best fit for this situation. Similarly, all values for the link budget will need to be updated with the actual values for the flight SDR radio on-board the ISS.

Following the model and algorithm development, the next step will be to develop the receiver

in Simulink and Xilinx. In the receiver design, the algorithm for waveform switching needs to be developed. Most importantly will be settling on an acceptable BER threshold to meet. The amateur radio community might have some values with justifications for thresholds. Finally, the receiver will be tested in FPGA implementation and then installed on the flight SDR for on-orbit testing aboard the ISS. Ultimately, the findings in this project will be tested against real data from the International Space Station and the propagation model will be either confirmed or refined. The on-orbit testing will provide data to evaluate the performance of the developed propagation model and algorithm.

8 References

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Navigating Export Control Reform

The Collaboration of AMSAT and Virginia Tech in Small-Sat Research

Sonya Rowe (KK4NLO)

1 Introduction to the Hume Center

The Ted and Karyn Hume Center for National Security and Technology was established in late 2009 with an endowment from Virginia Tech alum Ted Hume, who received his degree in Electrical Engineering in 1975. Through a cooperative education program offered by the university he went on to an esteemed career in the intelligence community before providing services to the community as a contractor and then as a consultant (Raboteau, 2010). His personal experience made apparent the need for the intelligence community to recruit talented, technical graduates who have an interest in serving their country and are able to obtain security clearances. The College of Engineerings Department of Electrical and Computer Engineering (ECE) was a natural home for the Hume Center which, due to rapid inter-disciplinary growth moved fully under the Institute of Critical Technologies and Applied Sciences (ICTAS) in 2013.

The Hume Center now comprises twenty affiliated faculty representing Electrical and Computer Engineering, Computer Science, Aerospace and Ocean Engineering, Business, Civil and Environmental Engineering; fourteen full-time research faculty and six professional program managers. Currently fifty graduate students are funded by Hume Center sponsored research. Research areas focus on signals intelligence, electronic warfare, cybersecurity and analytics, and aerospace systems. At the undergraduate level the Hume Center supports 150 students through a variety of scholarships and educational opportunities including the NSF CyberCorps Scholarship for Service program, the SAIC National Security Education Program, the IC Scholars program, and the Association of Old Crows Electronic Warfare scholarship. Virginia Tech is recognized by the Office of the Director of National Intelligence as an Intelligence Community Center for Academic Excellence, which offers both undergraduate and graduate students research, travel, and lecture experiences, as well as financial scholarships.

2 AMSAT – Virginia Tech Collaboration

The Hume Center made a critical strategic move in June 2011 by hiring Dr. Bob McGwier as the Director of Research. With this acquisition the center gained decades of experience in the intelligence field, an enthusiasm for technological advances (particularly in wireless communication), and an advocate and mentor for students headed for service in national security. McGwier also brought his long-standing relationship with AMSAT to Virginia Tech. This union was formalized in 2013 with a collaboration agreement designed to enable cooperation on the Fox-1 project (to be discussed in greater detail elsewhere in these proceedings). For Virginia Tech's part the collaboration

agreement was vetted through the Universitys Office of Sponsored Programs and contained the following language to define the nature of the partnership:

> WHEREAS, the above identified parties, because of their diverse capabilities, have determined that they would benefit from a collaboration agreement between the respective organizations in order to: encompass the development of space flight hardware, software, algorithms, documentation of same and an agreement to protect each other by protecting ITAR-covered materials and work and identifying same for the other.

Note the two critical elements of the agreements defining statement. One element delineates the types of collaboration to occur between Virginia Tech and AMSAT, which is expected and primary. But nearly as important as the definition of the collaboration, and of sufficient importance to be uttered simultaneously, is the statement expressing the mutual responsibility to correctly identify and protect ITAR information. The placement of this statement (which is fully expanded in section 12 Export and Sanctions Compliance) is consistent with both a deliberate (and warranted) caution by AMSAT to engage in any activities that may involve information subject to complex federal regulation and the universitys rigorous conformation to that regulation.

Virginia Tech's commitment to allowing innovative research to flourish within the confines of an increasingly hostile environment for proprietary and national security information is embodied in the Office of Export and Secure Research Compliance (OESRC), which is dedicated "to complying with U.S. laws and regulation applicable to export and trade sanctions" (Tech, 2015). OESRC accomplishes this by having a current and thorough understanding of export policy, maintaining a university policy that conforms to federal and state regulations, and getting involved early in any research that may be subject to those regulations. OESRC has developed a variety of mechanisms to ensure compliance including university and individual project Technology Control Plans (TCPs), Restricted Research Agreements, training, and access to a secure server for internal and external collaboration. These mechanisms, along with OESRCs professionalism have allowed for compliance and security awareness to be fully integrated into all research activities and have been indispensable as navigating ever-changing regulatory waters becomes increasingly complex.

In May of this year the collaboration agreement was updated to reflect continuing work on the Fox-1 project, as well as anticipated work on the HEO and GSO projects.

3 Export Control Reform

In 2013 US export regulations went through a massive overhaul, redefining many of the items and technical data that are of interest to researchers and amateur satellite radio operators. From 1993 to 2013 all satellites were controlled as defense articles under the International Traffic in Arms Regulations (ITAR), with no exception. Although requesting an export license was theoretically possible, the regulations made it virtually impossible to share information and engage in collaborative innovation with non-U.S. entities when it came to satellite design and operation. Post 2013 reform, export-controlled satellites are now defined more specifically by United States Munitions List Category XV Spacecraft and Related Articles (State, 2015), and must meet at least one of the following 13 conditions to be controlled under ITAR:

(a) Spacecraft, including satellites and space vehicles, whether designated developmental, experimental, research, or scientific, or having a commercial, civil, or military end-use, that:

1. Are specially designed to mitigate effects (e.g., scintillation) of or for detection of a nuclear detonation;
2. Autonomously track ground, airborne, missile, or space objects in real-time using imaging, infrared, radar, or laser systems
3. Conduct signals intelligence (SIGINT) or measurement and signatures intelligence (MASINT);
4. Are specially designed to be used in a constellation or formation that when operated together, in essence or effect, form a virtual satellite (e.g., functioning as if one satellite) with the characteristics or functions of other items in paragraph (a);
5. Are anti-satellite or anti-spacecraft (e.g., kinetic, RF, laser, charged particle)
6. Have space-to-ground weapons systems (e.g., kinetic or directed energy);
7. Have any of the specified electro-optical remote sensing capabilities or characteristics;
8. Have radar remote sensing capabilities or characteristics (e.g., active electronically scanned array (AESA), synthetic aperture radar (SAR), inverse synthetic aperture radar (ISAR), ultra-wideband SAR), except those having a center frequency equal to or greater than 1 GHz but less than or equal to 10 GHz and having a bandwidth less than 300 MHz;
9. Provide Positioning, Navigation, and Timing (PNT) signals;
10. Provide space-based logistics, surveillance, assembly, repair, or servicing of any spacecraft (e.g., refueling) and have integrated propulsion other than that required for attitude control;
11. Provide for sub-orbital or in-space human habitation and have integrated propulsion other than that required for attitude control;
12. That are not commercial communications satellites and that have integrated propulsion other than for attitude control or achieving initial orbit;
13. Are classified, contain classified software or hardware, are manufactured using classified production data, or are being developed using classified information (e.g., having classified requirements, specifications, functions, or operational characteristics or include classified cryptographic items controlled under USML Category XIII of this subchapter). "Classified" means classified pursuant to Executive Order 13526, or predecessor order, and a security classification guide developed pursuant thereto or equivalent, or to the corresponding classification rules of another government or international organization.

For a complete understanding of the current definition of controlled spacecraft and related articles please refer to the U.S. Department of State Directorate of Defense Trade Controls which lists in exhaustive detail special notes and additional information regarding these definitions.

Another aspect of export control reform is the concept of "specially designed" as defined in the Code of Federal Regulations Part 120.41:

a) Except for commodities or software described in paragraph (b) of this section, a commodity or software (see §120.45(f)) is *specially designed* if it:

   (1) As a result of development, has properties peculiarly responsible for achieving or exceeding the controlled performance levels, characteristics, or functions described in the relevant U.S. Munitions List paragraph; or

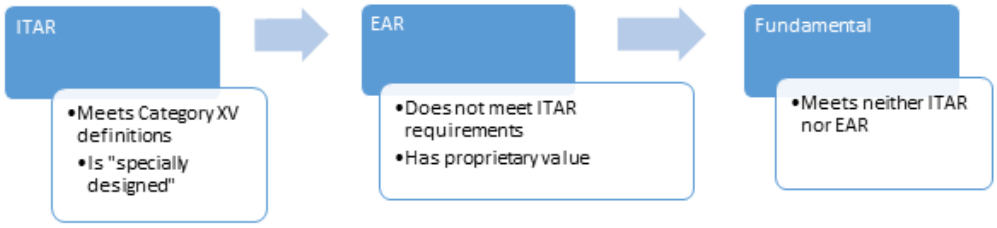

Figure 1: Commodity Jurisdiction Process

(2) Is a part (see §120.45 (d)), component (see §120.45(b)), accessory (see §120.45(c)), attachment (see §120.45(c)), or software for use in or with a defense article.

(1) Is subject to the EAR pursuant to a commodity jurisdiction determination;

(2) Is, regardless of form or fit, a fastener (e.g., screws, bolts, nuts, nut plates, studs, inserts, clips, rivets, pins), washer, spacer, insulator, grommet, bushing, spring, wire, or solder;

(3) Has the same function, performance capabilities, and the same or "equivalent" form and fit as a commodity or software used in or with a commodity that:

(i) Is or was in production (i.e., not in development); and

(ii) Is not enumerated on the U.S. Munitions List;

(4) Was or is being developed with knowledge that it is or would be for use in or with both defense articles enumerated on the U.S. Munitions List and also commodities not on the U.S. Munitions List; or

(5) Was or is being developed as a general purpose commodity or software, i.e., with no knowledge for use in or with a particular commodity (e.g., a F/A-18 or HMMWV) or type of commodity (e.g., an aircraft or machine tool).

For our purposes the specific list of spacecraft in Category XV, combined with the definition of specially designed provide a "catch and release" mechanism. An item that would appear to be controlled under the more restrictive ITAR can be relegated to the less restrictive control of the U.S. Department of Commerce Export Administration Regulations (EAR). If a space-related item is released to the EAR, and determined to have no proprietary value, it can be considered fundamental research and shared openly and relieved of regulatory control.

The formal process that determines whether an article may be released into the public domain is a "commodity jurisdiction request", made to the U.S. Department of State. OESRC has extensive experience and full time professionals dedicated to making these requests.

The impact of the reforms on amateur and academic satellite research is that there are now opportunities to engage in collaborative efforts in spacecraft development, particularly the increasingly popular small-sats, which had been almost completely diminished due to strict regulations. This does not mean that our communities must not still be cognizant of the existing restrictions in fact it requires perhaps even more diligence than was necessary prior to the reforms. The partnership of AMSAT and Virginia Tech is precisely intended to maximize creativity while minimizing the risk of export violations.

4 Conclusion

The purpose of this discussion is not to provide a tutorial on the intricacies of export control regulations but rather to emphasize the value of leveraging the expertise of security professionals, allowing innovative researchers in academia and amateur radio community to collaborate productively and without fear of divulging intellectual property or sensitive national security information. What we know for certain is that export control will only become increasingly complicated as globalization and security collide, but that complexity should not be accepted as a deterrent to technological advancement. AMSAT and Virginia Tech now find ourselves uniquely placed at the intersection of academia, national security and amateur pursuit and well-positioned to continue to flex the boundaries of human knowledge not in spite of, but embracing regulation as shield behind which innovation will continue to thrive.

5 References

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ARISS 2015 Status Report

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Stefan Wagener, VE4NSA; and Rosalie White, K1STO

Abstract

2015 has been a year of growth and change for the ARISS Program. Last year ARISS lost all support from NASA education. As a result, the ARISS-US team, in concert with NASA, restructured its support within NASA to keep ARISS alive. This year we are working with the ARISS international team to focus our strategies—our vision, mission, development, operations and external engagement—to sustain and grow ARISS into the future. Achieving sustainment and long-term growth will require close relationships, capital and in-kind support from our space agency partners, the amateur radio community, corporate and strategic partners. It will also require writing and winning grant proposals from foundations to move our objectives and goals forward. This paper describes the ARISS activities and events that were accomplished this year and presents an overview of ARISS' sustainment and growth fundraising initiative that is currently underway. It should also be noted that ARISS international celebrates its 15th year of continuous operation later this year and its 20th anniversary as an international team in late 2016.

Developing ARISS International Strategies and Initiatives to Sustain and Grow the Program

Overview

When NASA Education lost the bulk of its flight projects funding in 2014, NASA Education's Teaching from Space (TFS) Program ended its partnership with ARISS. This resulted in the loss of education and administrative support personnel from NASA that were supporting ARISS and the loss of financial support for our NASA operations manager (Kenneth Ransom). When ARISS received the cancellation notice, we spent the rest of 2014 and the beginning of 2015 shoring up the program to keep it alive. We are now positioning ARISS for sustainment and long-term growth, through numerous strategic initiatives. These initiatives will improve our partner, stakeholder and donor communications, bolster our on-orbit systems and educational processes to improve our educational outcomes and enable us to garner capital (dollars) and in-kind support (launches, expert help, etc), to sustain and grow ARISS.

Sustainability Goals

To clarify what sustainability means to ARISS, we have defined the following 2015-2017 sustainability goals:

- Obtaining resources (corporate funding, in-kind support, donations) and using these resources in a manner that ARISS continues for years in the future
- Developing a business plan, a business development team and a budget that will enable ARISS to grow and thrive into the future
- Nurturing strategic partnerships with organizations that will help ARISS achieve its strategic goals and to grow and thrive

These are crucial goals because funding from NASA and the other space agencies is

not guaranteed. We need to continue our efforts to garner space agency support (capital and in-kind), but must recognize that the bulk of our support may not come from the space agencies.

To accomplish the above goals, ARISS International has recently commissioned a Sustainability and Funding Committee. This committee was developed to define and implement business development and fundraising strategies in the pursuit of sustaining and growing ARISS. Current members of the committee include:

- Frank Bauer KA3HDO (USA), Chair
- Oliver Amend DG6BCE (Europe)
- Stefan Wagener VE4SW (Canada)
- Tatiana Kolmykova (Russia)
- Kiego Komuro JA1KAB (Japan)
- Convener: Rosalie White K1STO (USA)

NASA Relationship

Our relationship with NASA has changed, somewhat, and, in some cases, improved. In a nutshell, this is our status with NASA:

- We have established a long term strategic relationship with the NASA Space Communication and Navigation (SCaN) organization
- The ISS Program Office has been very supportive. They are working with us to develop formal partnering agreements with NASA, they recommended a partnership with Center for the Advancement of Science in Space (CASIS) and they ensured continuity to April 2016 through one-time funding of six months of Kenneth Ransom's task
- We have also strengthened our relationship with NASA HQ OIIR (Office of International and Interagency Relations), which provides a more thorough coordination and visibility of ARISS's contacts into NASA and NASA's external partners.

SCaN: Our Primary NASA Customer

Within NASA, our primary customer is SCaN. Of all NASA's organizations, ARISS and AMSAT's goals and strategies most closely align with SCaN. Thus, it makes sense for SCaN to establish a close partnership with ARISS.

Specifically, SCaN:

- Is responsible for all NASA's space communication, including ISS
- Is responsible for NASA's ground stations & TDRS communications relay satellites
- Provides NASA spectrum management leadership
- Has the largest segment of amateur radio operators within NASA
- Sees the importance of ARISS for their promotion of human spaceflight awareness and as a backup communications capability for ISS
- Since 2014, has been providing ARISS six months of funding per year for Kenneth Ransom's task.

As a result of our synergies and the need to keep the backup communications capability intact, SCaN has included ARISS as a line item in their long-term budget. For more information on SCaN, please go to: http://www.nasa.gov/directorates/heo/scan/index.html

CASIS

Another key partnership that we are growing and maturing is with the Center for the Advancement of Science in Space (CASIS). (http://www.iss-casis.org)

Based on a proposal that ARISS sent to CASIS in July 2014, CASIS is now working with ARISS in the pursuit of future corporate funding and in-kind support.

Some background on CASIS:

- In 2011, NASA chose CASIS as the sole

manager of the International Space Station U.S. National Laboratory

- The ARISS equipment in the Columbus Module is within the US National Laboratory
- CASIS' mission is to maximize the use of ISS for innovation, which can benefit all humankind and inspire a new generation to look to the stars
- To accomplish these goals, CASIS has:
  - Seed money
  - Expertise to help develop & integrate payloads and support educational outreach
  - Access to launch
  - Administrative support

Engagement with CASIS is still a work in progress. However, CASIS is starting to get ARISS in front of organizations that can seriously support ARISS from a capital and in-kind perspective. As an outsider with initially little knowledge of ARISS, they have helped us generate a "Frequently Asked Questions" (FAQ) document that can help potential donors understand our program, especially those with little knowledge of amateur radio. They have also helped us generate a generic proposal template to facilitate the development of proposals to donors or foundations. These are outstanding first starts of what may be a lasting relationship.

Funding Priorities and Strategies

ARISS's funding priorities are as follows:

1. Ensuring operations consistency through funding the Payload Manager/Payload Liaison Kenneth Ransom)—URGENT
2. Interoperable Radio System/Columbus Module Radio Upgrade—CRITICAL
3. Travel expenses: essential for international collaboration and hardware development
4. Operations & Technical Support: Supports collection of metrics & student release forms, development of program schedule, meeting preps, configuration management, overall team coordination

Fundraising strategies:

Step 1: Continue maturing the partnership with CASIS

- Coordinate with CASIS on the development of promotional materials, such as conference posters (complete), presentation materials, information packets and donation handout materials
- Develop a donation solicitation strategy (partially complete), ultimately garnering corporate funding, foundation grants and support for flight hardware certification and launch of ARISS hardware systems

Step 2: Solicit ARISS donations through the www.amsat.org website using the "ARISS donate" button on the AMSAT main page.

- We have initiated a fundraising campaign. Those that participate and donate $100 or more will receive an ARISS Challenge Coin.
- Target: International general public, including hams, and families and friends that have participated in an ARISS contact

Step 3: Seek travel funding or in-kind airline travel trips (domestic and international). Initial strategy will target donations from airlines

Step 4: Develop and evolve networking strategy, to improve probability of donor success. Target:

- Events (Including annual ISS Conference)
- Foundations
- Individuals

Sustainability and Fundraising Summary

ARISS is working aggressively as an

international team to focus our strategies—our vision, mission, development, operations and external engagement—to sustain and grow ARISS into the future. We have adapted and improved our relationships and funding stability within NASA, we are working with the other international space agencies on capital and in-kind support, we have commissioned an ARISS sustainability and funding committee to focus our strategies, we have partnered with CASIS and are working with them to develop and improve our fundraising strategies and priorities and we are working with CASIS to maximize our probability of winning future proposal submittals. We currently have acquired funding (through SCaN) that will sustain ARISS until April 2016 and are following up on a promising lead that will keep our ops task funded to October 2016.

Despite the significant challenges of the past, there appears to be a bright future for ARISS, as long as we work diligently to garner in-kind and capital funding through partnerships and corporate and foundation sponsorships. Our exceptional educational outreach impact, outstanding volunteer team and strong international partnerships are key elements in sustaining ARISS. Our success thus far has been the result of the tremendous dedication of the ARISS team, particularly the many volunteers world-wide that make the ARISS Program feasible and so successful.

It is important to note that if the ARISS Program is to remain alive, to be sustained, and to grow, it is critically important that the program develop a team that can garner outside support—in-kind and real dollar support. This will require individuals with skills in business development, fundraising and networking. If you have these skills or are willing to learn, please contact Frank Bauer ka3hdo@verizon.net.

2015 Highlights

Tokyo Meeting

An ARISS International delegates meeting was held at the Big Sight convention facility located in Tokyo, Japan from Thursday August 20 until Sunday August 23. This ARISS face-to-face meeting was held in conjunction with the Japan Amateur Radio League's 90th anniversary celebration and International Ham Fair Exposition.

ARISS-International face-to-face meetings are periodic gatherings of ARISS Delegates and representatives from the five regions that support the development and operations of the amateur radio systems on board the International Space Station: Canada, Europe, Japan, Russia and the United States.

The meeting covered various facets of the ARISS program, including international teamwork, technical systems development and amateur radio operations on ISS. Included in the meeting agenda were committee reports, technical project updates, upcoming contact events, reports on ARISS activities within the five represented regions and special award recognitions to the JARL, the Japan Aerospace Exploration Agency (JAXA) and JVC Kenwood.

The meeting kicked off with a presentation by Hideshi Kagawa from JAXA on their initiatives to launch and deploy small satellites and technology payloads using their low-cost Epsilon launcher.

Much discussion during the weekend centered around fundraising and the formation of the ARISS-International Sustainability and Funding Committee. Funding projects and recommended yearly budgets were discussed. ARISS Chairman Frank Bauer encouraged all ARISS Regions

to begin supporting the development of an international plan and strategy for funding and resources. This will be accomplished through the Sustainability and Funding Committee.

A discussion on a revision of the organization's current Terms of Reference (TOR) was conducted. This new TOR will better formalize and document team roles, responsibilities and processes and will address other more recent changes within the ARISS program. Delegates voted to study the feasibility of creating an interoperable radio system based on the Kenwood D710 radio that would be interchangeable between the Columbus and Russian ISS modules. It was also agreed to continue studying the implementation of an Astro Pi Slide Show and Slide Show module for use in conjunction with the development and operation of the Ham TV system on board the ISS.

During their stay, the group also engaged in other activities such as a ribbon cutting event kicking off the beginning of the JARL Ham Fair and celebrating the 90th Anniversary of the JARL, attending JARL 90th anniversary events, including a Welcome Reception, conducting a very productive Technical Meeting with JVC Kenwood Engineers on the D710/interoperable radio system proposal, and touring JAXA's Tsukuba Space Center and their ISS/Kibo control center.

During the visit, the ARISS-International team took time out to recognize three organizations that have provided sustained support and service to the ARISS program--JARL, for nearly 20 years of ARISS delegation support, JAXA for their sustained support as an ISS space agency, and JVC Kenwood for their leadership in modifying the D700 and D710 radio systems to support ARISS current and future operations. All three organizations received a beautiful, autographed photo montage of the astronauts using ARISS on-board ISS and an ARISS pin and sticker that flew on the last Space Shuttle mission, STS-135.

Before concluding the meeting, ARISS delegates voted to hold its next annual meeting in Houston, Texas in November 2016. This date coincides with the 20th anniversary of the inaugural ARISS working group meeting, held November 1996 at the NASA Johnson Space Center in Houston, Texas.

The meeting ended with a heart-felt thank you to all team members. It is clear that ARISS is working tightly together as an outstanding world-wide team.

Canada Highlights

Within Canada, Steve MacFarlane, VE3TBD and Brian Jackson, VE6JBJ, are active in serving ARISS Operations, while Stefan Wagener, VE4SW, represents AMSAT-NA as the Canadian Delegate and Ian MacFarquhar, VE9IM, represents RAC as the Canadian Delegate on ARISS-I.

Thanks to the dedication of our mentors, coordinators and delegates many exiting things have happened during the 2014/15 timeframe and are a true reflection of the Canadian team.

From July 1st to Dec 31st 2014, Steve MacFarlane, VE3TBD was the lead in scheduling and coordinating ARISS contacts on behalf of ARISS-I. Thanks to Steve and his efforts a number of successful contacts were accomplished.

Within Alberta, Brian Jackson accomplished four teacher conference presentations and

three teacher workshops. In addition to working on future Canadian school contacts, Brian is supporting the ARISS "Point of Contact" list and completing a review of all members and their current information and status.

In 2015, VE4ISS, the new and only Canadian telebridge station in Winnipeg, Manitoba, was put into operation and received final "certification" by providing a successful test contact with Samantha Cristoforetti, IZ0UDF. Both the telebridge backup system and the primary system were exercised as part of a successful contact with the Tulsa Community College contact on July 1st, 2015.

VE4ISS is hosted at Shaftesbury High School and is the first high school based telebridge station within the ARISS-I network. The station is operated by Grade 9-12 students who all are licensed amateur radio operators and provides for a new ARISS-I service where students serve students around the world connecting to the ISS. VE4ISS would not have been possible without the dedication and support by the teachers, Rob Striemer, VE4SHS and Adrian Deakin, VA4AMD the school principal Stan Wiebe, the Pembina School Division, the Radio Amateurs of Canada (RAC), Prairie Mobile (Winnipeg Kenwood Dealer) and the Winnipeg Amateur Radio Club (VE4BB). The local mentor is Stefan Wagener, VE4SW.

Ian MacFarquhar, VE9IM facilitated the successful process for election of the ARISS-I officers in 2014.

Both Stefan and Ian attended and represented the Canadian Team at the international ARISS meeting in Japan in August of 2015.

One of the future challenges with the ARISS Canada team is to again reconnect with the Canadian Space Agency (CSA) since the CSA has extended their commitment and support to the ISS up to 2024.

Operations Highlights

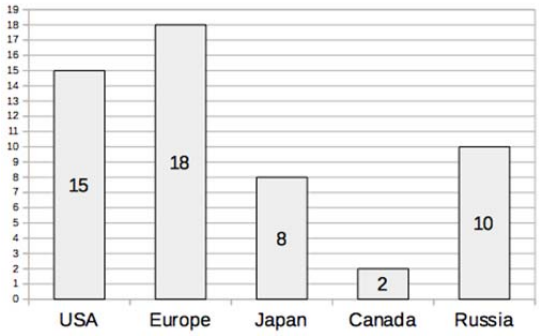
Educational Contacts

During the past year (October 1, 2014 to September 30, 2015), ARISS conducted 53 successful contacts in 20 countries. US contacts occurred in 10 states plus Guantanamo Bay. For comparison, in the preceding year we conducted 72 contacts in 17 countries and 16 states.

Overall, about 62% of contacts involved a ground station at the students' location. This is slightly below the average of 67%.

Through strong international teamwork, this past year we worked with our colleagues from ARISS-Russia to have Russian crew members support non-Russian educational group ARISS events. This was critically important in maintaining contact momentum during those times when there were no US segment amateur radio operators on-board ISS.

Contacts by Region



SSTV Operations

The Russian ARISS team continues to run occasional SSTV special events from the Zvezda module. These events use the Kenwood D710 radio and a laptop running

MMSSTV software. SSTV events have celebrated the Russian Space program in December 2014 and February 2015, Cosmonautics Day (Yuri Gagarin's flight) in April 2015, and the 40th anniversary of the Apollo-Soyuz joint mission in July 2015. A team in Poland created special diplomas (certificates) for those who received images during these events. Selected images from these events can be viewed here: http://spaceflightsoftware.com/ARISS_SSTV/index.php.

Cosmonautics Day Commemorative

SSTV operation is part of an on-going experiment called "About Gagarin from Space". Transmissions have used the PD180 mode. There is a possibility that PD120 will be used for future events, to allow reception of more images per pass.

Ham TV Operations

During the past year, operational control of the Ham Video equipment was transferred from ESA to ARISS. This was accomplished through signature of an ARISS-ESA agreement to transfer over Ham-TV operations and custodianship to ARISS. That opened the way for transmissions in "blank transmission" (BT) mode. In this mode, the transmitter is operated without a camera. The digital TV signal is fully formatted, but the content of the video is black and the audio is at zero level. From a technical perspective, a BT signal is all that is needed for ground stations to test and fine-tune their receive system.

BT mode is active whenever on-board operations permit. It must be turned off for spacecraft docking and undocking and when the MAGVECTOR experiment is underway (it and Ham Video share a power receptacle). When European stations are receiving BT transmissions, you can find the digital video on the British Amateur Television Club (BATC) server at http://www.batc.tv/iss/.

Ham Video Transmitter for the Ham TV System

Initial Ham TV operations will use a chain of Ham TV ground stations in Europe (separate from the telebridge network) to provide a continuous 10 minutes of video coverage on both ascending and descending passes over Europe. These stations are continuing to test reception and improve the system of linking and streaming video over the Internet. When the ground system is working reliably, a test of the entire Ham TV system (DATV video and audio down, VHF audio up) will be conducted.

After gaining some operational experience with Ham TV, we expect to expand the Ham TV ground network to include chained stations in North America and possibly elsewhere.

You can find the latest information and status on Ham TV on the ARISS-Europe website (www.ariss-eu.org) and the ARISS-International website (www.ariss.org).

Backup Communications

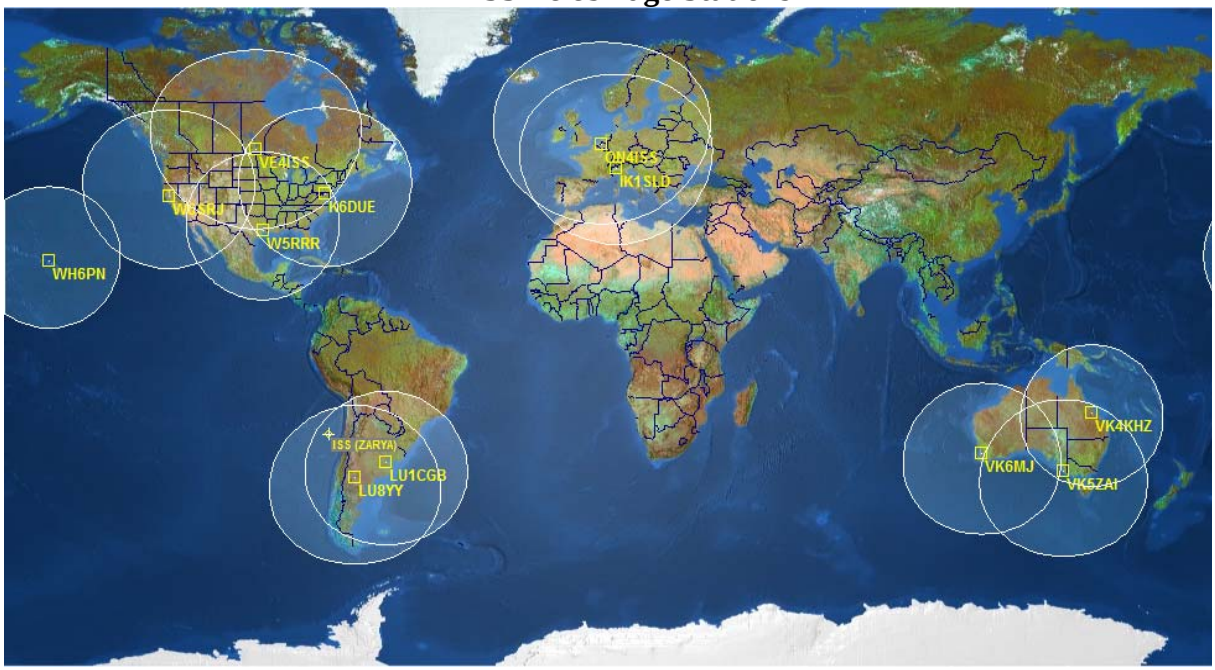
One of the original roles of ARISS is being re-energized, thanks to our new relationship with NASA's Space Communications and Navigation (SCaN) office. We are currently reviewing our existing procedures and will be making plans for practice exercises to prepare the telebridge network and the ham community to assist NASA in the event of an ISS communications failure.

which has a new location and operator. Four of the other stations currently have limited or no use for reasons such as maintenance and operator availability.

Volunteers Needed

The US operations team is looking for additional help with several jobs, particularly with technical guidance to schools (mentors). We also need someone familiar with Python to modify and help test an upgrade to our custom orbit prediction software. If you are interested in helping in any way, contact Dave at w8aas@amsat.org.

ARISS Telebridge Stations



Telebridge Network

There are 12 designated telebridge stations in the ARISS network. In July this year, we added VE4ISS, a student-operated station at Shaftesbury High School in Winnipeg, Canada. We are awaiting a checkout contact with ISS to reactivate ON4ISS in Belgium,

Educational Activities

Proposal Solicitations

With the departure of the Teaching from Space office, AMSAT and ARRL manage the proposal process for all US contacts. We have modified the process to address some

issues and improve results. (For details, see the paper *The New and Improved ARISS Proposal Process* in these Proceedings.)

The US team has conducted two solicitations using this process in the past year and a third is underway as this paper is written. The first solicitation was opened in October 2014 and selected 15 schools, one of which later withdrew. The 14 remaining schools are receiving ARISS contacts in the last half of 2015. The second solicitation opened in March 2015, with 14 schools being selected for contacts in the first half of 2016.

A list of US schools completed in the past year appears at the end of this paper. Currently, the other four regions of ARISS (Europe, Japan, Canada, and Russia) use the original application process to select schools. However, Europe has announced plans to begin using a proposal process, modeled on the US process, called EuroSchools. They are currently scheduling two schools per contact in order to work through a large backlog of waiting schools, and will start their new process when the backlog is exhausted.

Educational Outcomes

ARISS receives many comments from educators whose students have made outstanding educational achievements after participating in an ARISS contact. These comments illustrate the impact ARISS has on students and their education, and we've shared many of these in the past. The following comment is unusual, in that is comes from a teacher whose class only *listened* to *another* school's ARISS event.

Comment from Elsie Martinez, 2nd grade teacher in Laredo TX, to Principal Dan Mateo at Bio-Tech High School (which hosted the contact), January 15, 2015:

"My students are 7-8 years old and while they are very young, I was able to see how watching this live feed sparked curiosity and interest in them. They were attentive during the viewing and full of questions when it was over. Some asked to know more about the astronauts in space. Others wondered what it is like to be a student in your school and have the privilege of learning science with hands-on field work. I, as an educator, especially enjoyed listening to one of your students ask Miss Cristoforetti about her education and the importance it played in her career. It led my classroom discussion into their future plans and reinforced the message that an education is necessary, and that with an education and perseverance, they can achieve greatness. It is never too soon to expose these children to the possibilities that are out there. After watching and discussing the video, they began talking among themselves about how exciting it would be to visit space or work for NASA."

Tim Peake Mission

United Kingdom astronaut Tim Peake, KG5BVI, will launch to ISS in December of this year. The UK Space Agency reported that Astronaut Tim Peake wants to work with ARISS to talk to a minimum of three schools, hopefully more from all over the world. Ciaran Morgan, M0XTD, from ARISS-Europe is coordinating these efforts and has worked with ARISS and the Tim Peake team on many excellent educational activities and educational venues to tie in to ARISS. There is also a potential long-term connection with the Astro Pi/Raspberry Pi capability that will fly as part of Tim Peake's "Principia" education mission.

Hardware Development

ARISS has several hardware projects in

various stages of development. This section provides a brief overview of current activities.

Interoperability Initiative

Most of the ham radio equipment aboard ISS was developed with a single location in mind. Because certification rules and power sources differ between the US Operating Segment (120 VDC) and Russian Segment (28 VDC), our equipment cannot be moved between segments. ARISS has developed guidelines to assure that all future hardware can be used equally well anywhere aboard ISS. This will provide the flexibility to move radios wherever needed as requirements change.

Upgraded Radio System

Since beginning to conduct educational contacts from the Columbus module, ARISS has seen the need for a higher-power radio than the 5-watt Ericsson radio that is approved for use there. Work is underway to replace the Ericsson with an upgraded system. This system has two components:

- A modified Kenwood D710G transceiver
- An ARISS-built low-voltage power supply that can provide correct voltages for the D710G, the Ham Video transmitter and camera, and future equipment from an input of either 120 or 28 VDC

We are now meeting to specify the operating configuration and needed modifications for the D710G. Engineers from Kenwood are assisting with the design. The design team has prepared a block diagram of the power supply that was presented to the Delegates at their recent meeting in Tokyo. The next step is to identify funding and build a prototype. More details on this interoperable radio upgrade are available in the paper *Interoperable Radio System Upgrade* in these proceedings.

Ham TV Enhancements

The success of the Ham TV system so far has prompted discussions on increasing its usefulness and availability. Items being considered are:

- Slide Show and Camera unit based on the Raspberry Pi microprocessor. It would also provide a looping slide show from a file on a standard USB stick and would allow for continuous Ham TV transmission. This would increase the opportunities to receive Ham TV on the ground for developing and testing ground stations.
- Multifunctional Beacon comprised of an S-band CW beacon with telemetry and a transponder function (L-band up and S-band down).

Preliminary designs exist for these items and are being revised to meet review comments.

Summary and Conclusions

2015 has been a year of substantial growth and change for the ARISS Program. The ARISS international team is working aggressively to focus our strategies, including our vision, mission, development, operations and external engagement so that we can sustain and grow ARISS into the future. Our ARISS team relationship continues to be strengthened by international face-to-face meetings, most notably our recent meeting in Tokyo. Our relationship with NASA has improved and has expanded. Our primary NASA customer is SCaN, whose goals and ideals are synergistic with those of ARISS and AMSAT. SCaN is now providing funding as an essential element of our sustainment strategy. Our relationship and communi-cation with the ISS Program Office has grown and improved. We are also working with the other international space agencies on capital and in-kind support.

We have commissioned a sustainability and funding committee to focus our strategies and have partnered with CASIS to develop and improve our fundraising strategies and priorities. This will help us maximize our probability of winning future proposal submittals. Also, our hardware team is aggressively pursuing an upgraded higher power radio system for the Columbus module that will be designed and certified to be interoperable throughout all of ISS. This capability will improve school contacts, providing and even richer educational activity.

Despite the significant challenges of the past, there appears to be a bright future for ARISS, as long as we work diligently to garner in-kind and capital funding through partnerships and corporate and foundation sponsorships. Our exceptional educational outreach impact, outstanding volunteer team and strong international partnerships are key elements in sustaining ARISS. Our success thus far has been the result of the tremendous dedication of the ARISS team, particularly the many volunteers world-wide that make the ARISS Program feasible and so successful.

Dedication

The ARISS team would like to dedicate this paper to three outstanding ARISS volunteers that have poured out their support into ARISS and Human Spaceflight but passed away this year. Specifically, we would like to dedicate this paper to Nick Lance, KC5KBO, Max Canepa, IW1CNF, and Bill Pasternack, WA6ITF.

Nick Lance, KC5KBO was an ARISS-US team member who also worked for NASA. Nick was our primary astronaut trainer and his infectious enthusiasm and unique teaching talents inspired countless astronauts to obtain their amateur radio license. His “Hamster” classes also engaged numerous students in amateur radio activities and enabled many to obtain their amateur radio license.

Max Canepa, IW1CNF was an ARISS-Europe team member and IK1SLD telebridge technician. Bill Pasternack, WA6ITF, through the years, chronicled astronaut’s use of amateur radio on the Shuttle, Mir and International Space Station via Newsline and through his contribution in many ham radio video productions.

Bill, Max and Nick are greatly missed.

US Educational Contacts in the Past Year

School	City	State	Type
Indiana Area School District	Indiana	PA	telebridge
The Explorers Club	New York City	NY	telebridge
Richmond Heights Middle School	Miami	FL	direct
Council Rock High School – South	Holland	PA	direct
Riversink Elementary School	Crawfordville	FL	direct
East Coast Chapter Tuskegee Airmen, Inc., Youth In Aviation Program/Oxon Hill HS	Oxon Hill	MD	telebridge
Tulsa Community College, NE Campus	Tulsa	OK	direct
Kopernik Observatory & Science Center	Vestal	NY	direct
Moon Day/Frontiers of Flight Museum	Dallas	TX	telebridge
United Space School	Seabrook	TX	telebridge
Space Jam 9	Rantoul	IL	telebridge
Pima County 4H/Vail Vaqueros 4H Club	Tucson	AZ	direct
Maconaquah School Corporation	Bunker Hill	IN	direct
New Mexico Military Institute	Roswell	NM	direct

Interoperable Radio System Upgrade

September 30, 2015

Prepared by Lou McFadin and Mark Steiner

Overview: In January 2015 a team investigated the replacement of the Ericsson radio currently in the Columbus Module with a more capable radio. The top candidate was to provide a Kenwood D710 radio with any needed power supply modules. The team has been meeting roughly twice a month through 2015, and the result is a proposal for consideration by the Project Selection and Use Committee with a recommendation to the ARISS-I delegates for consideration at the face-to-face meeting in Japan in August 2015.

Members: The team consists of the following members:

Mark Steiner	Chair
Lou McFadin	ARISS Chief Engineer
Stefan Wagener	Member
Dave Taylor	Member
Kenneth Ransom	Member
Kerry Banke	Member
Frank Bauer	Ex-officio

Actions: The team developed a top-level design considerations document that was the basis for an input to a proposal to CNES to obtain a dedicated Portable Power Supply (formerly known as "KUPS") that would convert the ISS 120 VDC to 28 VDC. Since that proposal, the team has refined the design to consider two options for power supplies, the use of a dedicated PPS and the use of an ARISS-developed power supply.

The result is a robust system that will provide interoperability in the Russian Segment (FGB and Service Module) and the US Operating Segment (Columbus Module). Any portion of the proposed system could be operated in either segment with proper cabling. It would also allow any other ARISS systems that are certified in one segment to be operated in the other segment, after proper certification.

Top-level system requirements:

1) Launch Kenwood D710 radio and supporting elements so ARISS-I has a high-power radio in the Columbus Module (COL) that is compatible with the D710 radio in the Russian Service Module (SM).
2) All components shall be able to be used interoperability across all the ISS segments.
3) Include a power supply that can interface with the existing system in the Columbus Module (including the Ham TV) and be flexible enough for future systems.
4) Be compatible with the other ISS Ham system components (headsets, SSTV module, antennas, etc.), with connector adapters, if necessary.

5) Allow the D710 to be re-programmed on-orbit. Options to be considered are a small dongle, an Apple iPad with standard ISS software load or a Windows tablet.
6) Provide enough flight-like hardware for training and system certification.
7) Include power system pass-troughs to maintain flexibility to bring in other options/future systems.
8) Provide flexibility for current and future capabilities/modes:
    a. Cross-band repeater
    b. SSTV
    c. Packet/APRS/Other digital techniques
9) Minimize crew time
    a. Provide options for possible later addition of remote control of system from the ground (provide interfaces, not necessarily implement at this time)
10) Minimize volume in ISS Columbus Module.
11) Ensure systems meet ISS and equipment thermal control
    a. Power supply
    b. D710

System Description:
The proposal consists of these components:

- ARISS AMSAT-NA-developed and built Low Voltage Power Supply (LVPS) that includes the capability to convert directly from either from the ISS 120 VDC or 28VDC
- Kenwood D710 transceiver
- necessary cables
- certifications
- procedures.

See Fig. 1.

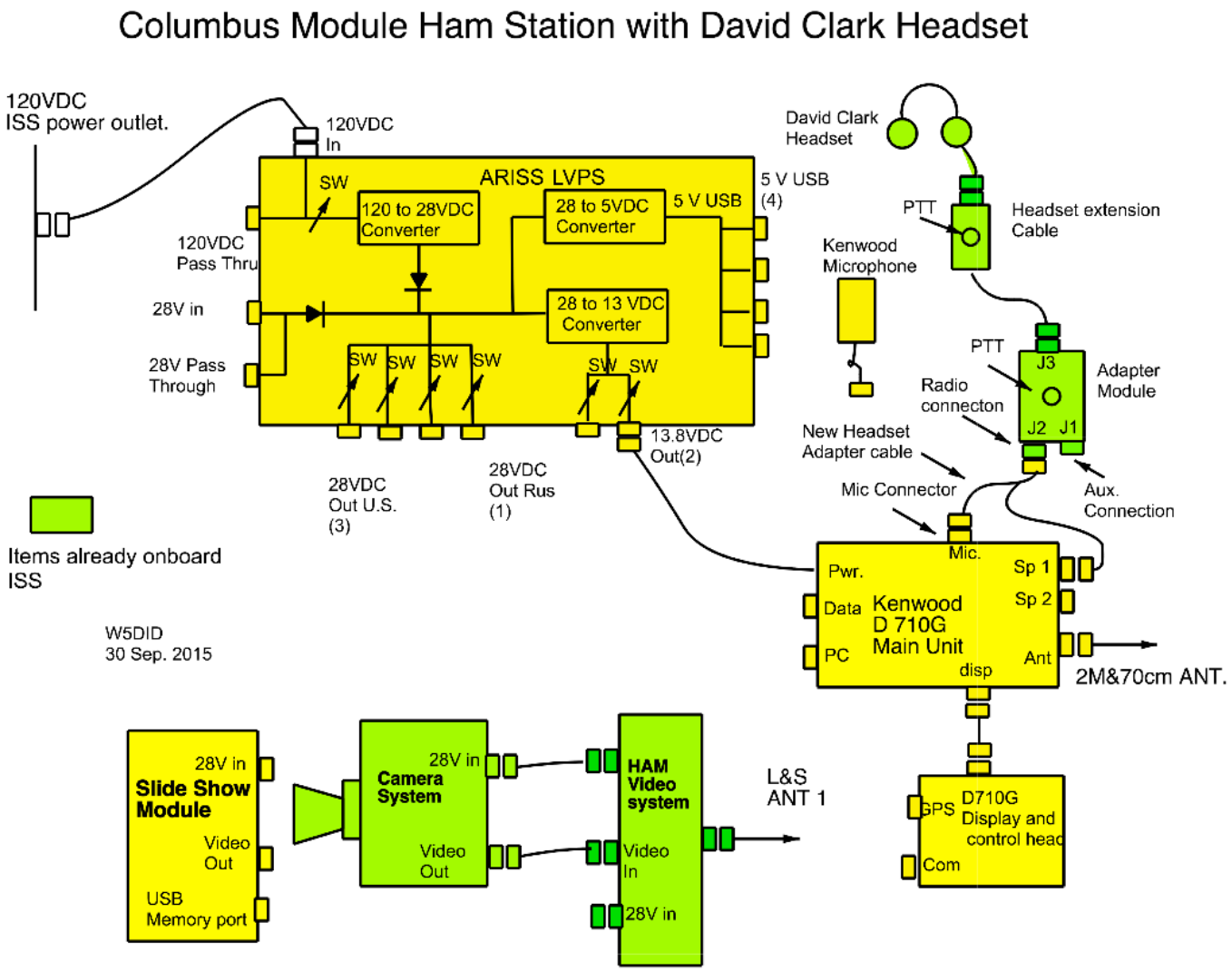


Fig. 1 - Proposed system block diagram

ARISS Low Voltage Power Supply (LVPS) description:

This unit converts either the 28 VDC provided by the PPS or the 120 VDC provided by the ISS to the voltages needed for the actual inputs of the rest of the ARISS-I hardware. It would provide 13.8 VDC for the Kenwood D710 and 5 VDC at 2.1 A for a set of four standard USB connectors for charging USB devices. It would also provide pass-throughs for the 120 VDC and 28 VDC for additional equipment connections (so we do not tie up a 28 VDC connector), 3 standard US 28 VDC connectors and one standard Russian 28 VDC connector. This would allow for the interoperability of Russian hardware in the Columbus Module.

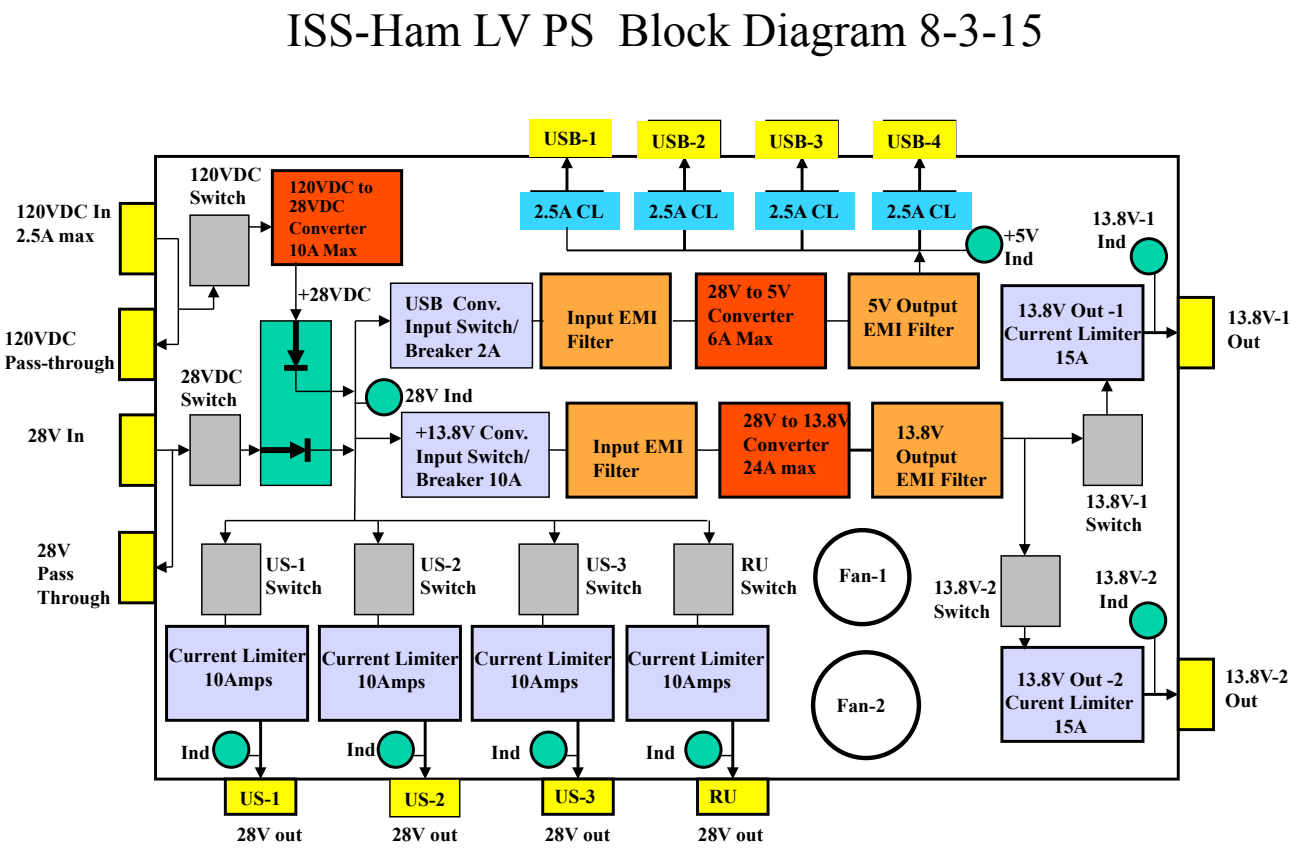


Fig. 2 – Low Voltage Power Supply more details

The D710 plan:

The ARISS hardware team, including Bob Bruninga, has been working with JVC Kenwood engineers to develop a plan for the version of the D710 radio to be used on the ISS. This will be a slightly modified version of the D710G sold in the US market.

The Kenwood D710G in the Columbus Module will have some differences from the D710 that is currently in the Russian Segment:

1. It will have either a heat sink and fan to allow continuous operation or it will be configured to physically attach to the new LVPS (Low Voltage Power Supply). In that case the extra airflow from the LVPS will enable continuous operation of the D710G. The firmware changes will allow a longer timeout period to support cross band repeater function.

2. The D710G already has a simpler command set for entering the cross band repeat mode.
3. It will have different connectors for power, etc.
4. We may include a firmware modification to reduce maximum power output to 25W.

Launch mass estimates for whole system:

	Mass (kg)
PPS	3.97
28V Low-Voltage Power Supply	4.00
Kenwood D710	1.86
Cables	2.00
Total	11.83

Other considerations:

For each flight component (except the PPS) there shall be the following 7 units, all identical to the flight unit:

1 - Flight
1 - Flight spare
3 - Training (1 for US/JSC and 2 for Russia)
2 - Engineering (2 units), for trouble-shooting, procedure development, etc.

Conclusion

The capability of the ARISS hardware onboard the ISS is continuously evolving.

These changes will make it easier for the crew due to simpler setup procedures. The quality of school and other contacts will be improved due to the higher RF power capability. The capability for supporting contingency backup for the ISS com system is improved due to the higher power and the interoperability in both the US and Russian segment. This system builds upon past experience and hardware by re-using existing cables and equipment such as the David Clark Headset and Russian power cables.

By incorporating the David Clark Headset into this design, we provide a new level of flexibility that has not been available to the crew.

We are planning for the present needs and for the future needs. This new power supply and improved D710G are important components in that evolution.

This concept was presented to the ARISS-I delegates and attendees at the recent Tokyo meeting and was given their approval to continue with its development.

The New and Improved ARISS Proposal Process

By Frank Bauer, KA3HDO, AMSAT VP, Human Spaceflight and ARISS Program Chairman; Debra Johnson, K1DMJ, ARRL Manager Education Services; E. Michael McCardel, KC8YLD, AMSAT VP, Education Relations; Mark Steiner, K3MS, NASA Technical Liaison; Dave Taylor, W8AAS, AMSAT Delegate to ARISS Int'l; Rosalie White, K1STO, ARRL Delegate to ARISS Int'l

Presented by E. Michael McCardel

In the first half of 2014, NASA's Education Office made the decision to no longer fund its Teaching From Space (TFS) Program. At the time TFS was the primary NASA partner and education liaison for ARISS. One of TFS' roles was to lead the school proposal and selection process in the USA. Except for finding ways to fund existing support personnel, the loss of TFS served as an opportunity for AMSAT and the ARRL to take a hard look at our current education proposal process and improve it. As the new process would be done exclusively by ARRL and AMSAT, it significantly reduced the bureaucratic burden that encumbered the ARISS-USA team when TFS led the effort. This was due to the government requirement to get approval from Congress for all education requests for proposals, including ARISS. As part of the new proposal process, the ARISS-USA team identified several ways we could make requests for ARISS contacts more competitive, with more emphasis on educational content, media outreach and with an improved method for meeting the technical aspects for conducting a contact.

This presentation was prepared to bring AMSAT membership up to speed with how the ARISS proposal process for the United States works. It is built upon the existing Proposal Guide to which every school or educational organization refers when preparing their proposals. The guide is included herein. My presentation highlights the application and preparation process as well as the challenges ARISS is expecting these institutions and organizations to achieve before, during and after the contact.

In addition to this presentation we hope to enlist volunteers to assist in several opportunities to work with the ARISS teams. Here are some of the volunteers we need:

Mentors

Because of some of the changes made to the process we judge that Mentors are taking on more responsibility and time for each scheduled contact. For that reason we hope to recruit additional Mentors to relieve some of the burden of our existing Mentors as well build skills and knowledge for the next generation of Mentors.

Pass Prediction Software Developer

The current pass prediction software needs to be upgraded to work with current operating systems.

Researchers

We need information miners to research existing lesson ideas and plans and how they relate changing curricular standards to meet required STEM objectives.

Website Designers and Content Writers

We need people to help develop communications/content for external audiences as well as write and maintain the information developed for the ARISS website

Survey Metrics Administrator

We need someone who will track our statistics and evaluations as well as follow up with institutions that have completed contacts to make sure their surveys are submitted in a timely fashion and to obtain photos, videos and talent releases.

The ARISS Proposal Guide:

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Preface

Who Should Use This Guide

This Proposal Guide is for educators interested in hosting an Amateur Radio on the International Space Station (ARISS) contact in the United States and its territories. Before initiating a proposal please visit www.arrl.org/ARISS for a complete description of the program.

About ARISS

What is ARISS?

Amateur Radio on the International Space Station (ARISS) is a cooperative venture of the Radio Amateur Satellite Corporation (AMSAT), the American Radio Relay League (ARRL) and the National Aeronautics and Space Administration (NASA) in the United States, and other international space agencies and international amateur radio organizations around the world. The primary purpose of ARISS is to organize scheduled contacts via amateur radio between crewmembers aboard the International Space Station (ISS) and classrooms or informal education venues. With the help of experienced amateur radio volunteers from amateur radio clubs and coordination from the ARISS team, the ISS crewmembers speak directly with large group audiences in a variety of public forums such as school assemblies, science centers and museums, Scout camporees, jamborees and space camps, where students, teachers, parents, and communities learn about space, space technologies and Amateur Radio.

Goals of the ARISS program include:

- Inspire an interest in science, technology, engineering and math (STEM) subjects and in STEM careers among young people
- Provide an educational opportunity for students, teachers and the general public to learn about space exploration, space technologies and Amateur Radio as preparation for the event
- Provide an opportunity for amateur radio experimentation and evaluation of new technologies

- Provide a contingency communications system for NASA and the ISS crew.

- Provide crew with another means to directly interact with a larger community outside the ISS, including friends and family.

ARISS United States Partners

NASA: NASA provides access to onboard ISS resources, including the on-board crewmembers, supports the launching of hardware, provides educational resources and supports mission planning for ARISS contacts.

AMSAT: AMSAT provides program leadership, technical support, and resource coordination (both US and international) to successfully conduct the ARISS program. AMSAT is responsible for the US development, operation and maintenance of the on-board hardware. AMSAT interacts with the national space agencies to provide expertise and guidance about amateur radio in space. AMSAT provides experienced volunteers who serve as ARISS Technical Mentors, guiding organizations through their technical execution of an ARISS contact.

ARRL: ARRL sponsors an educational outreach program that provides resources for students and teachers to explore radio science and wireless technology and to engage students in these and other STEM topics. ARRL also is part of the ARISS program leadership team, providing program guidance and administrative support. ARRL coordinates ARISS applications from US schools and organizations.

Read more about the international ARISS program partnership at: www.ariss.org/about.html.

What is an ARISS Contact?

An ARISS contact is an opportunity for students and educators to interact with the crew aboard the International Space Station (ISS) through a 10-minute question and answer

session using amateur radio. ARISS contacts are large-scale, public events and are ideal for a variety of forums such as school assemblies, science centers and museums.

Though the ARISS contact itself is only a 10-minute event, the educational plan leading up to and following the event is much more extensive. Host organizations are expected to plan and execute an effective educational plan over a week, month, semester or school year that engages relevant content areas such as (but not limited to) space exploration, technologies related to space research, space communications and wireless technologies, and amateur radio as a hands-on learning focus. Educational plans focusing on this content will prepare students for a fuller appreciation of the ARISS contact event and can extend to further exploration of the space and radio/wireless technology topics following the actual event.

Why does NASA support ARISS contacts?

ARISS contacts use the unique experience of human spaceflight to afford audiences the opportunity to learn first-hand from space explorers what it is like to live and work in space. These events are designed to encourage students to study and pursue careers in STEM.

In addition, ARISS provides an opportunity for students, teachers and the public to learn about wireless communications technologies and the capabilities of amateur radio, encouraging students to further explore these technologies.

This Proposal Guide offers information about the process and requirements to host an ARISS contact. You may direct questions or comments to ariss@arrl.org.

Section 1: Getting Started

Fitting the Opportunity

Is my organization a good fit for this opportunity?

An ARISS contact may be a good fit if your organization:

- Is a formal or informal education institution or organization
- Has the ability to adapt to ARISS date and time changes, understanding the constraints of the planning timeline
- Has flexibility regarding pre- and post- ARISS contact educational activities
- Has the ability to develop a strong ARISS contact education plan
- Can secure a large student and educator audience
- Can assemble a team to handle the education, media, technical and evaluation components of an ARISS contact
- Has the ability to establish community partnerships, including a partnership with representatives of your local ham radio community

How do I maximize this opportunity?

Think of the ARISS contact as part of a much larger vision. Use the ARISS contact to:

- Bring STEM subjects alive for students through an educational plan that includes investigation of multiple topics dealing with space exploration, space research, space and communications technologies leading up to and following the event
- Enhance or create new partnerships with local businesses and community leaders as well as other educational organizations
- Attract widespread attention to your organization
- Support local education objectives and initiatives

Understanding the ARISS Proposal Process

What do I do first?

The first step is to decide if your organization is a good fit for this opportunity. Read this Proposal Guide thoroughly.

Then what?

If you decide you want to proceed, begin with a proposal containing your education plan. Proposal forms are available at www.arrl.org/hosting-an-ariss-contact. Please note that due to limited contact opportunities, ARISS will approve proposals that best meet

the program's objectives. (Evaluation criteria are described in Section 2.)

Proposals to host an ARISS contact are evaluated and decisions announced during two cycles each year to plan for contacts that will be scheduled 6-12 months into the future. Find the details for the current proposal window at www.arrl.org/hosting-an-ariss-contact.

The ARISS proposal process is a two-step process.

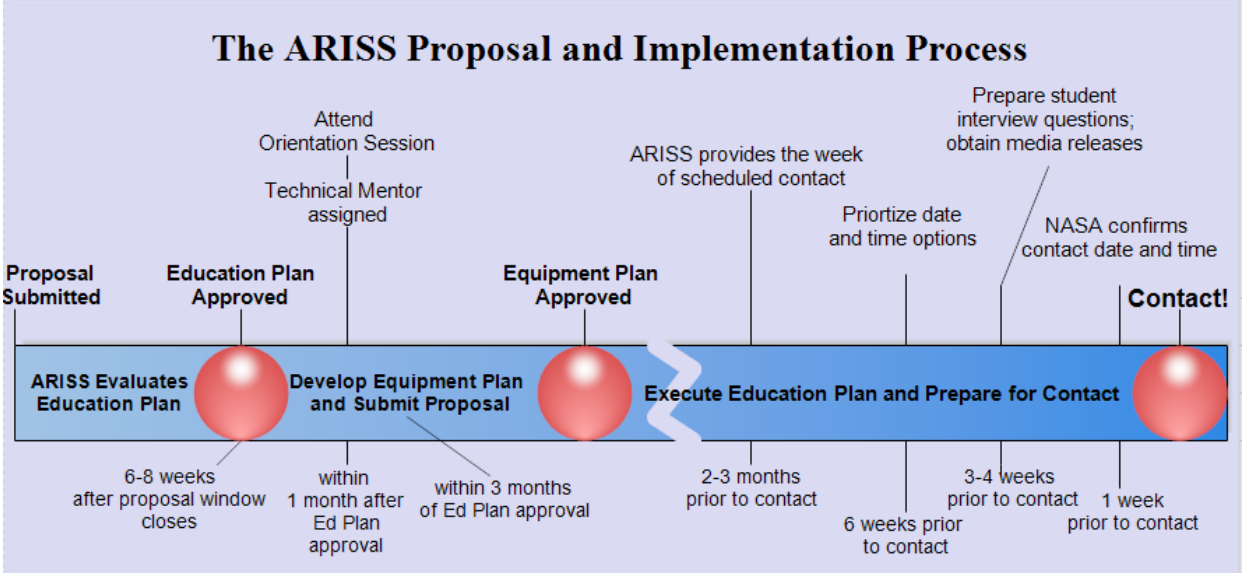
- Step 1 – Completion and approval of your Education Plan
- Step 2 – Completion and approval of your Equipment Plan

Details about the Education Plan and Equipment Plan appear later in this guide. After approval of both plans, your organization will be entered into the scheduling queue for an ARISS school contact. Bear in mind that your ability to execute your plan and also be available and flexible to respond to scheduling options provided by NASA for the radio contact are very important. Though we try very hard to provide scheduling options that align with your preferences, due to the nature of the program nothing can be guaranteed.

Once your Education Plan is approved (Step 1), an ARISS Technical Mentor will be assigned to work with your ARISS project team to help you develop your Equipment Plan (Step 2). The Technical Mentor is a volunteer amateur radio operator who is very experienced with satellite communications. He or she will help you and your local team of amateur radio operators develop a satisfactory Equipment Plan.

The Planning Timeline

The timeline and table below offer a broad outline of the major action and decision points in the preparation process for an ARISS contact. The Orientation Session and your Technical Mentor will provide details about specific activities and deliverables leading up to and after your contact.


The ARISS Proposal and Implementation Process
Attend Orientation Session
Technical Mentor assigned
ARISS provides the week of scheduled contact
Prepare student interview questions; obtain media releases
Priortize date and time options
NASA confirms contact date and time
Proposal Submitted
Education Plan Approved
Equipment Plan Approved
Contact!
ARISS Evaluates Education Plan
Develop Equipment Plan and Submit Proposal
Execute Education Plan and Prepare for Contact
6-8 weeks after proposal window closes
within 1 month after Ed Plan approval
within 3 months of Ed Plan approval
2-3 months prior to contact
6 weeks prior to contact
3-4 weeks prior to contact
1 week prior to contact

Summary of Proposal and Implementation Process

Submit Education Proposal	
Education Plan is evaluated and approved	Within 6-8 weeks after proposal window closes
Attend Orientation Session; receive Technical Mentor assignment	Within 1 month after Education Plan approval
Determine direct or telebridge contact and submit Equipment Plan	As soon as possible, but no later than 3 months after Education Plan is approved
Equipment Plan is approved; you are added to ARISS scheduling queue	
Implement Education Plan and prepare for contact	Within 1 month after Equipment Plan is approved
Learn the week of the scheduled contact: Confirm availability	2-3 months prior to contact
Learn the possible dates and times during the assigned week of the contact: Prioritize options	6 weeks prior to contact
Prepare student interview questions and obtain media releases for participating students	3-4 weeks prior to contact
NASA confirms contact date and time	1 week prior to contact. *Note*: this

	short window is dictated by NASA operations planning and is beyond our control

Section 2: The Educational Component

Creating an ARISS Education Plan

What is an ARISS education plan?

An ARISS education plan describes how the host organization will utilize the ARISS contact to enrich STEM learning activities, support local education objectives and the goals of the ARISS program. The plan should describe how the pre- and post-contact activities tie into the 10-minute live contact with the ISS crewmembers.

How can you integrate this activity into the school curriculum?

- Match activities with State and/or National Educational Standards
- Use an interdisciplinary approach to lesson development
- Utilize cross-functional teaching teams
- Engage multiple grade level participation
- Broadcast over school's LAN, CCTV or PA system and/ or Web
- Partner with local science-oriented organizations, such as museums, clubs, and industry
- Use year or semester-long space themes

What are some examples of classroom activities that can engage learning in preparation for the ARISS contact?

Here are some suggestions for classroom activities that can enrich the ARISS experience:

- Visit NASA web pages to find what research projects on the ISS the students find exciting

- Develop student projects related to a research project in the ISS National Lab
- Have students write a proposal for a research project they could like to conduct as an astronaut or a project for a space satellite
- Learn about other NASA space projects such as the Mars Lander Curiosity, Cassini, Voyager, the Hubble Telescope, the James Webb Space Telescope
- Research the biographies of astronauts
- Research the ISS communications systems
- Investigate the many uses of the radio spectrum and how it is managed
- Create posters about space
- Establish an amateur radio club
- Practice amateur radio operation protocols
- Broadcast a daily space fact over the PA system
- Explore careers related to space exploration and space technologies
- Learn about satellite orbits and orbital mechanics
- Build an antenna for satellite communications
- Involve students in the set up and operation of the ground station for the contact
- Find out when the ISS will orbit over your town and watch it pass overhead
- Invite guest speakers who work in science and technology fields
- Investigate radio science fundamentals
- Investigate electronics fundamentals
- Use satellite-tracking software to track orbits
- Write a story about life in space

The Addendum to this Guide provides references to educational resources you can utilize to build your Education Plan.

Elements of a Strong Education Plan

What are some tips to completing a strong education proposal?

- Brainstorm creative ways to maximize the ARISS contact reach and experience for students.

- Determine your educational objectives and plan a comprehensive educational program of which the ARISS contact is only one component.
- Incorporate partnerships that have a lasting impact on the community.
- Integrate NASA Education and amateur radio content with educational activities (links to a variety of NASA and ARRL resources are provided in this guide).
- Include an outline of the STEM activities and topics appropriate to the grade level of your students you will engage as part of the learning and preparation for the ISS contact.
- Describe how you will select the interview questions and students who will conduct the interview with the crewmember.
- Establish an evaluation plan that will help you determine whether you are accomplishing your objectives and the goals of the ARISS program.
- Keep date flexibility in mind. ARISS contact dates are driven by ISS mission requirements and are tentative due to the nature of human spaceflight.
- Proofread your proposal to make sure the information is complete and relevant.

The more advance preparation you make with educational plans, the more learning and value the ARISS event will have for students. Preference will be given to plans that demonstrate careful thought and appropriate integration of STEM topics at student grade levels.

Evaluation of the Education Plan

Who will evaluate your plan?

Representatives from each of the US ARISS partners confer twice each year to review proposals submitted during the two proposal windows. Decisions on education proposals will be announced by email to the main point of contact who has submitted the proposal no later than 6-8 weeks following the close of the proposal window.

How will the education plan be evaluated?

The evaluation team will weigh heavily on how well your proposal submission addresses the following points:

- **Education**
    - Is the ARISS radio contact and surrounding comprehensive education plan beneficial to the education community?
    - Does the plan advance (enhance) the students' engagement in science, technology, engineering and mathematics (STEM)?
    - Does the education plan include STEM and amateur radio activities?
    - Does the education plan include NASA resources and mission-related content?
    - Is the plan developed to extend over a period of time to increase and extend the impact of the ARISS contact for students in your audience?
    - Does the plan describe the student groups/grades that will be part of the education plan? What are the demographics of this group? What student groups/grades and other audiences will be part of the audience for the contact event?
    - Have all educational organizations that are described as plan participants been involved in developing the plan and are they committed to carrying it out?
    - How does your educational plan build upon your school's curricular objectives and how does the contact opportunity support your school's curricular objectives?
- **Logistics**
    - Does the proposal demonstrate flexibility should an ARISS radio contact shift dates and/or times?
    - Does the proposal provide a clear overview of the contact including location that accommodates a large number of students, audience, transportation (if needed), and technology (audio/video/Internet and radio station)?

- **Outreach**
    - Does the proposal include a detailed media/outreach plan?
    - Does the proposal include plans to involve the community in the ARISS radio contact and/or education plan?

Section 3: The Technical Component

Understanding Amateur Radio Technology

How are ARISS contacts performed?

An amateur radio contact with the space station is a line of sight contact between an amateur radio ground station and the amateur radio station on board the ISS. Your interview with the astronaut will utilize either a ground station at your location for a direct contact, or a ground station at another remote location for a telebridge contact.

- A **DIRECT** radio link between an amateur radio station set up in your venue and the amateur station onboard the ISS. Direct contacts are timed such that the ISS is passing over your location.
- A **TELEBRIDGE**, in which an ARISS amateur radio ground station, located somewhere in the world, establishes the radio link with the ISS. Voice communications between your students and the ground station travel over regular telephone lines.

Preparing for an Amateur Radio Contact

How do I prepare for an amateur radio contact?

Preparation is different for direct and telebridge contacts.

A **direct** contact will give your students an opportunity to use an amateur radio station at your location to speak with astronauts. It will also provide a first-hand opportunity to see an amateur radio station and learn how the radio system works. It will more clearly show the students the physics of spaceflight and orbits as the radio station will be tracking the position of the ISS with its antennas as the ISS flies overhead of your school. For direct contacts, local amateur radio operators or clubs work with the host organization to set up radio station equipment and antennas that provide a clear line of sight to the projected path of the space station.

If you are unable to arrange a direct contact, a **telebridge** contact can also be a rewarding experience for students and your community. ARISS amateur radio

telebridge ground stations enable ISS radio contacts with organizations that are unable to support a direct contact. This may be due to the ISS not passing over the school's location except during the night, or passing over at an elevation that is too low for a good radio contact, or other technical concerns. In a telebridge contact, one of the ARISS amateur radio telebridge ground stations around the world establishes the radio link with the crew member using the ISS amateur radio station.

For either direct or telebridge contacts, your local amateur radio operators, your ARISS Technical Mentor and the ARRL's education resources can provide training with amateur radio operations and educational resources you can use to explore radio science and communications technologies with your students.

It is important to reach out to your local ham radio community as you prepare your Education Plan. Discuss your educational objectives and your plan with them to determine their ability to support you with the expertise, equipment needs and instructional support for learning activities related to amateur radio. Get their commitment of support.

If you have trouble identifying a local ham radio club to support your efforts, contact the ARRL at ariss@arrl.org for assistance.

What equipment do I need to have in place for a direct contact?

Local amateur radio operators or clubs in your community can work with your organization to set up the necessary radios and antennas for a direct contact.

Briefly, for direct contacts, antennas are configured to provide a clear line of sight to the projected path of the ISS. Typically, this means the antennas are on the roof where the fewest obstructions are located. Because the ISS is 240 miles above Earth and traveling at 17,500 miles per hour, it will cross the sky from horizon to horizon in about 10 minutes. This path defines the communications footprint. During this time, the beam antennas must track horizontally (azimuth) and vertically (elevation). Due to the motion

of the ISS, the radio frequency must also be corrected for the Doppler shift. By doing the Doppler shift correction, the audio clarity will be maintained as clearly as possible.

The recommendations for the ground station to support a direct contact are considerably more robust than needed for a casual point to point radio contact. Because the scheduled contact is a one-time event involving a large audience, every effort is taken to configure a ground station that will offer the maximum communications window possible within the constraints of orbital mechanics and line of sight considerations, and to provide redundancy in the event of unexpected equipment failure.

If you are considering a direct contact please review the current ARISS Ground Station Recommendations with your local amateur radio technical team. Find the current recommendations at www.arrl.org/hosting-an-ariss-contact.

What equipment do I need to have in place for a telebridge contact?

Two separate, dedicated telephone lines are required for telebridge contacts. The first telephone line serves as the direct communications line. The second telephone line (which can be a cell phone) serves as a backup in case there are any failures or technical issues with the first telephone line. Discuss recommendations for a suitable telebridge configuration with your Technical Mentor.

Can other people listen in on the contact?

Other schools, institutions, and radio amateurs are encouraged to listen in on contacts. There is a standard downlink frequency for the events. If listeners happen to be in the ISS footprint, they can hear portions of the ARISS contact. Listeners can only hear the crew member answers, not the student questions, which are communicated on a separate frequency. The ARISS team shares the students' questions ahead of time so all listening in the ISS footprint or on the Web can follow along. Many host organizations stream the interview over the Web to make the entire interview available to students who are not on site for the event.

The Equipment Plan

What is involved with the Equipment Plan?

After your Education Plan has been approved, you must decide whether your contact will be executed direct, with a ground station on site, or by telebridge. You must develop an Equipment Plan that provides the information necessary to be sure you will be able to support the contact method you have chosen. Your Technical Mentor will assist you and your local ham radio team to help you work through the considerations. You will be expected to provide the information requested on the ARISS Equipment Plan Form. You can download the form at www.arrl.org/hosting-an-ariss-contact. Your Equipment Plan must be completed and submitted as soon as possible after your Education Plan has been approved, but no later than 3 months after approval. Your contact with the ISS will not be submitted for scheduling until your Equipment Plan is reviewed and accepted by the ARISS management team.

Section 4: The Media/Outreach Component

What is a media/outreach/promotion plan?

A media/outreach/promotion plan is an overview of how the host organization plans to communicate information about the amateur radio interview and surrounding educational activities out to your community. The plan should describe plans for both internal and external promotion.

Some strategies to consider:

First promote within your school/organization!

What you are attempting to achieve is a program that will pull together all of the students, teachers, school staff, and much of your community in a single unified goal…a personal interview with a crew member on the ISS using amateur radio... that has stimulated students' interest in science, technology, math, and engineering (STEM).

It is very important to garner support from school administrators, principals, and superintendents. They can also offer services in obtaining media attention.

Parents

Remember to include parents and parent groups in your plans. Not only do they help encourage students to complete their part of the ARISS educational activities, but they can play a role in having the media see the importance of the event to the community.

Parents may be given the assignment of recording events (audio, video, note-taking, photographs) as they unfold. Parents can get quotes from students and teachers about the learning activities leading up to the ARISS contact and the impact on their outlook. Enlist the help of parents and their students in distributing programs for the ARISS contact day, and in seating VIPs and the media.

Business Leaders and Community VIPs

Business leaders and local VIPs can offer help in a variety of ways. For some it might mean offers of various media exposure, printing of invitations, t-shirts for students, or simply demonstrating support for the students. Create and distribute special invitations to local VIPs.

Other Schools and Educational Groups

Invite neighboring schools to listen in to the radio contact from a remote location. Even better, invite them to attend your educational activities and ARISS contact. Provide a special seating area for them.

Involve Students

- Students can be selected to write articles describing their learning activities for the school paper, local paper, and other media.
- Create programs to be distributed on the day of the event to all who attend. These become great keepsakes. They can also help to communicate some details about the event.
- Work with students so that they will be prepared to speak to the media after the radio contact. Prior practice doing this can be helpful for students.
- Select students for specific responsibilities such as publicity, art work, production of event programs and invitations.
- Select students for the responsibility of recording all of the school's activities and lessons, including the day of the contact.

How do we involve local news media?

You will want to make sure that you inform your local news organizations about your upcoming interview with the ISS. You will need to notify them in advance about the planned event and keep them informed as you have more details about the date and time the contact will occur. It is important to designate someone within your organization as the point of contact with media to make sure that accurate and timely information is provided. You might consider inviting the media to tour your school before the ARISS

contact to see what students have been learning. Be sure to emphasize the educational impact of the opportunity.

- Send news releases to newspapers, TV stations, radio stations once the date of the contact is known. Get a sample press release at www.arrl.org/hosting-an-ariss-contact and customize it for your venue.
- Ensure you have collected the required permission forms from all students who will be participating in the ARISS contact who will be interviewed, recorded, or photographed by the media. You'll find a release form you can download and print at www.arrl.org/hosting-an-ariss-contact.
- Send links for newspaper articles, television stories and other website stories to your ARISS Technical Mentor so we can communicate the story about your event to the organizations that fund ARISS.
- Send photos and scanned release forms for students photographed to ariss@arrl.org.

Addendum: Resources for Education

Accessing NASA Resources

What kinds of NASA educational resources are available from NASA?

NASA produces a variety of resources for educators and students. These resources include websites, printed materials, student programs and professional development opportunities. The NASA Education resources listed below will help with writing the proposal and the creation of activities.

NASA Education Home Page

http://education.nasa.gov

This site serves as a gateway to information on NASA Education programs and services for educators and students. Educators can search for resources by grade level, topic, and type. The site contains numerous educator guides, posters and multimedia that will help provide information about NASA and space exploration that host organizations will find useful in planning activities for students.

NASA Digital Learning Network (DLN)

http://dln.nasa.gov

The goal of the DLN is to enhance NASA's capability to deliver unique content by linking students and educators with NASA experts. The DLN offers videoconferencing or Webcasting at no charge, providing interactive educational experiences to students and educators from kindergarten to university levels across the nation and around the world. Host organizations can utilize the DLN to connect to NASA for pre- and/or post-ARISS contact activities. DLN also has a special ARISS Module at www.nasa.gov/offices/education/programs/national/dln/events/HAM_It_Up.html for those interested in learning more about ARISS and amateur radio.

International Space Station (ISS) Home Page

http://www.nasa.gov/mission_pages/station/main/index.html

This site serves as the main homepage for the ISS. You can find the latest news on missions, ISS activities and resources.

NASA Space Communication and Navigation (SCaN) Home Page
http://www.nasa.gov/directorates/heo/scan/#.VCwZ5T_AbaJ
This site serves as the main homepage for SCaN, the NASA organization responsible for NASA's communications with satellites, including ISS.

What other NASA resources are available?
There are a variety of other NASA resources that host organizations could utilize in preparing for an ARISS contact.

Astronaut Appearance Requests
http://www.nasa.gov/about/speakers/astronautappearances.html#.VCsBhvldUnc
NASA astronauts appear before a variety of groups to inform the general public about the U.S. Space program. Requests must be submitted far in advance. There is a cost involved for the host, and appearances are very limited.

Astronaut and Cosmonaut Biographies
http://www.jsc.nasa.gov/Bios/index.html
The astronaut biography homepage provides information on the members of space flight crews and candidates for future missions in NASA's space flight programs.

NASAcast
http://www.nasa.gov/multimedia/podcasting/#.VCsBqfldUnc
Subscribe to NASA's omnibus podcast for the latest mission news, features and the "This Week @ NASA" report.

NASA Television
http://www.nasa.gov/multimedia/nasatv/
NASA TV is a resource designed to provide real-time coverage of NASA's activities and missions. NASA TV features ISS and Space Shuttle mission coverage, live special

events, amateur radio contacts, electronic field trips, aviation and space news and historical NASA footage.

Science at NASA
http://science.nasa.gov/
Find out the latest headline science news happening at NASA. Subscribe to *NASA Science News*, an electronic newsletter, to learn about new findings and developments in space research. This is a great way to get students tuned in to space research activities.

Accessing ARRL Education Resources

What kinds of resources are available from ARRL?
ARRL's Education & Technology Program offers three types of resources to teachers and schools. These include resources for instruction (including kits and projects), professional development opportunities and grants for radio stations and related equipment.

Education & Technology Program
http://www.arrl.org/education-technology-program
Resources are available for educators to use to help their students understand how an amateur radio contact with the ISS is conducted. Foundational concepts of wireless communications, radio waves, the electromagnetic spectrum, wave forms and modulation, satellite communications, orbits, and Keplerian elements are a few of the concepts discussed.

Teachers Institute on Wireless Technology
http://www.arrl.org/teachers-institute-on-wireless-technology
This Institute offers an expenses paid professional development opportunity, which provides hands-on training for educators to learn about basic electronics, wireless communications, micro-controllers, programming fundamentals and robotics and offers

resources for classroom instruction. Attending the Teachers Institute is a great way to prepare for an ISS contact through the ARISS program.

Listen to or Watch ARISS Contacts
http://www.arrl.org/listen-to-watch-ariss-contacts
This web page provides audio and video recordings of ARISS contacts that will give educators a good idea of how the contacts are conducted and the kind of conversations that develop between students and astronauts. A search on YouTube will produce additional video recordings of ARISS contacts.

Preparation for an ARISS Contact
http://www.arrl.org/preparation-for-an-ariss-contact
Resources collected on this web page will generate ideas for your education plan. You'll find resources here for learning about satellite communications, radio science, electronics and space travel and exploration and some sample education plans developed by other schools.

Using Amateur Radio in the Classroom
http://www.arrl.org/amateur-radio-in-the-classroom
This web page provides information on using amateur radio in the classroom as an effective way to teach both fact and theory. Amateur radio can be used to engage students in a variety of subjects. Visit the web page at www.arrl.org/curriculum-connections-and-benchmarks for ideas about how amateur radio subject content can align with state and national learning objectives. Additional ideas and resources can be found at: www.arrl.org/preparation-for-an-ariss-contact.

AMSAT Fox-1 Engineering Documentation Update

Compiled by Jerry Buxton, N0JY
AMSAT Vice President - Engineering
n0jy@amsat.org

AMSAT, as an educational organization, would like to publicly release the majority of our design documentation to serve as a learning tool to anyone interested in satellite development. However, in order to avoid complications with ITAR and Export Administration Rules, the information must first be released via an openly available publication. We would also like to be able to discuss our satellite projects with our own members, some of whom are not "US-persons" per those regulations. These AMSAT Space Symposium proceedings provide a convenient mechanism for the needed publication in order to make this information public domain and allow us to communicate with our members.

While many of the Fox-1 documents were published in previous *Proceedings*, some of these documents have undergone changes as the satellite design has progressed and evolved therefore the updated versions will be reproduced in these 2015 Space Symposium proceedings. In addition, these proceedings also present any new engineering documents that have been produced since the last publication which include some of the documentation for the Fox-1Cliff and Fox-1D satellites.

Through publication in the three proceedings, the majority of the Fox-1A documentation has now been introduced to the public domain.

Date: September 29, 2014
Version: 3.92

AMSAT *Fox-1*
Avionics System Design Specification

1 Introduction

This document contains the system level design specifications for the AMSAT *Fox-1* satellite avionics systems. It is driven by the System Requirements Specification and other documents provided by the developers of the individual systems that make up the satellite system.

1.1. Document History

DATE	VERSION	SUMMARY
February 21, 2012	1.0	From Draft F
April 9, 2012	1.1	Add signal characteristics, update bus pin connections per System Team input
April 17, 2012	1.2	Add external connector specification in sections 2.6, 2.12 and 2.14 and references in section 6
April 18, 2012	1.21	Add MMCX connectors gender
April 22, 2012	1.3	Minor corrections in signal characteristics, remove +Z antenna deploy and sensor connections
July 10, 2012	2.0	Many revisions from PDR
July 11, 2012	2.01	One RBF pin removed from bus pin assignments, updated 2.1 interconnect diagram, updated 2.1 signal characteristics
July 21, 2012	2.1	Revised bus signals, bus pin assignments Updated RF block diagram
July 22, 2012	2.11	Revision to some RF signal descriptions, change antenna/coax connectors to UMCC type, updated RF block diagram, added driving and load system columns to signal characteristics
September 9, 2012	3.0	Major changes.
September 11, 2012	3.01	Defunct IHU block diagram pending update
September 12, 2012	3.1	Added PCB volume requirements
September 23, 2012	3.11	Change TX PTT to RX PTT, -Z Deploy switches to TX, update figures and tables accordingly
September 26, 2012	3.12	Update bus and pin assignment drawings
September 27, 2012	3.13	Update bus pin assignment drawings
September 30, 2012	3.14	Update RF block diagram to remove ITAR notice
October 17, 2012	3.15	Import changes to requirements from System Requirements
February 17, 2013	3.2	Incorporate system bus signal nomenclature and pin assignment changes
February 28, 2013	3.3	MEC connector changed orientation (flipped) on +X -X +Y -Y panels.

DATE	VERSION	SUMMARY
March 28, 2013	3.4	Add second –Z PPOD deploy switch (pin 54), PPOD deploy switches now on TX system card
March 31, 2013	3.41	Updates to the TX, RX, IHU, and BUS pin diagrams.
March 31, 2013	3.42	Adjusted RESERVED pin colors only
April 21, 2013	3.43	Addition of RX Frequency Control, TX Frequency Control, and Sensor Power signals Pin reassignments: Moved pins 52 and 54 to pins 33 and 35 respectively Moved pins 40 and 42 to pins 29 and 42 respectively Added the above new signals to pins 42, 40, and 38 respectively
April 25, 2013	3.5	Update per System Requirements 3.10.2 changes. Updated bus connection pin assignments, bus interconnect diagram, and system bus signal characteristics account removal of TX OSC Temp and TX PA Temp and addition of TX Temperature
June 26, 2013	3.6	Add requirements for PSU and BATT1 CPU reset from RX Command Data, updated IHU block diagram
July 24, 2013	3.7	Add ALERT signal, SENSOR POWER signal, remove RBF2, rename RBF1 to Solar Safe N, remove RX Command Data connection from BATT1, flip MEC connector orientation on +X, -X, +Y, -Y panels, update ME-113 mechanical drawings
August 26, 2013	3.8	Rename RX OSC TEMP to RX Temperature, add Initial Surge Current Limits for certain systems, move Command Decoder to IHU system (bus pin changes), update some bus nomenclature, update System Requirements for each system per changes to the System Requirements
August 27, 2013	3.81	Correct source and destination for RX Command Strobe in Table 1
September 17, 2013	3.82	Add (move) RSSI to Pin 10, rename Pin 32 as RX CD, add Solar Power A and Solar Power B to pins 55 and 56, update TX Block Diagram, remove RX Command Data connection from PSU, update hyperlinks.
October 8, 2013	3.83	Remove IHU AUDIO OUT 2, RX AUDIO 2 signals, rename IHU AUDIO OUT 1 to IHU AUDIO OUT, RX AUDIO 1 to RX AUDIO.
November 11, 2013	3.84	Updated IHU Block Diagram
January 23, 2014	3.85	Add Sensor Power connection to PSU
January 23, 2014	3.86	Several text (requirements) changes to match recent System Requirements change for Safe Mode.
April 27, 2014	3.87	Add PCB plating requirements for TX, RX, IHU, PSU, BATT, EXP systems
May 29, 2014	3.88	Correct 6.7 to read PSU System
August 16, 2014	3.9	Updates to 5.1, 6.1 to match updated system requirements
August 20, 2014	3.91	Correct 5.1 to show 120 seconds for Safe Mode beacon
September 29, 2014	3.92	Update PSU block diagram, add receiver block diagram, update commands in 5.1, update instances of system requirements 3.9.3, 3.9.4, 3.9.6

1.2. Document Scope

The purpose of this document is to specify the avionics systems and their connections to each other and to external components for the satellite. It is intended to be used by the hardware, software, and mechanical designers to develop the architecture and interconnections for the satellite avionics systems.

1.3. Document Format

This document provides these elements in a numbered format. The numbered sections specify each major system in the satellite while numbered items for each system specify the external connections required and the number of lines for each connection. Satellite bus and external connections are further described in figures and tables.
Where System Requirements are reproduced their numbers are from the AMSAT *Fox*-1 System Requirements Specification.

1.4. References

1. AMSAT *Fox-1* ConOps
2. AMSAT *Fox-1* System Requirements Specification
3. AMSAT *Fox-1* Bus (Signal Connections Diagram)
4. AMSAT *Fox-1* Bus Pin Assignment
5. AMSAT *Fox-1* Avionics System Design Specification Spreadsheet
6. AMSAT FOX-ME-120_Z_TOPBOTT_SOLAR_PANEL.pdf
7. AMSAT FOX-ME-127_Y_SIDE_SOLAR_PANEL.pdf

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6 Power Supply System (PSU) 24
7 Battery System 36
8 Experiment Payload Systems 1 through 4 41
9 System Block Diagrams Reference 47
10 System Interconnection References 51

2 Avionics System Bus Signals, Characteristics, and Connections

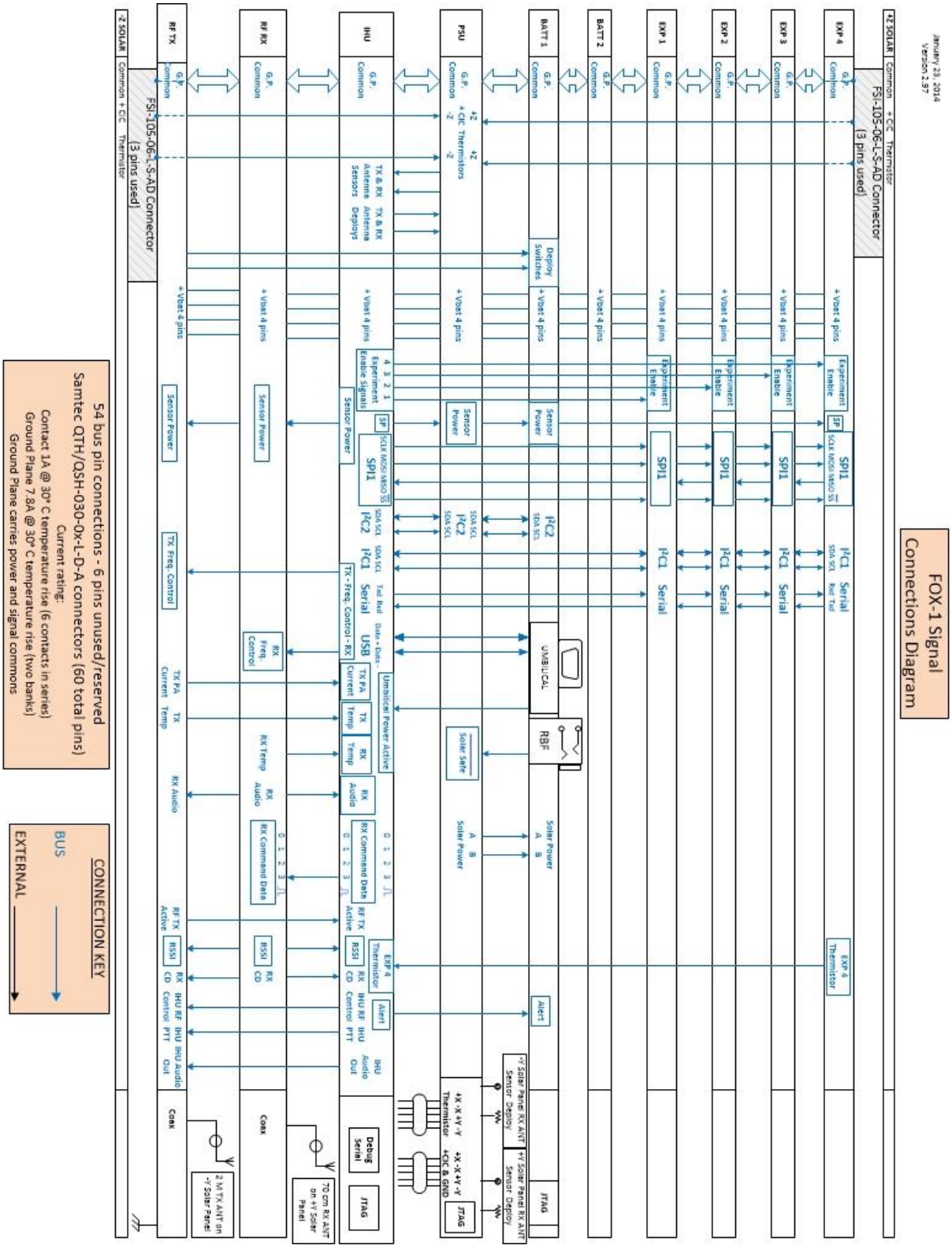

Figure 1: Interconnect Diagram

Table 1: System Bus Signal Characteristics

Pin	Nomenclature	Type	Voltage	Source System	Load Z	Load System	Notes
1	SPI1 NSS	Digital	Note[1]	IHU		EXP 1-4	SPI Standard, IHU Master
2	TX PA Current	Analog	0 - 3.0 V	TX	30 - 60 kΩ	IHU	
3	SPI1 SCK	Digital	Note[1]	IHU		EXP 1-4	SPI Standard, IHU Master
4	TX Temperature	Analog	0 - 3.0 V	TX	30 - 60 kΩ	IHU	Thermistor Circuit
5	SPI1 MISO	Digital	Note[1]	IHU		EXP 1-4	SPI Standard, IHU Master
6	Experiment 4 Thermistor	Analog	N/A	EXP 4	N/A	IHU	Temperature from Experiment 4 position
7	SPI1 MOSI	Digital	Note[1]	IHU		EXP 1-4	SPI Standard, IHU Master
8	RX Temperature	Analog	0 - 3.0 V	RX	30 - 60 kΩ	IHU	Thermistor Circuit
9	Serial RXD	Digital	3.0 V	EXP 1-4		IHU	Async, Mark High
10	RSSI	Analog	0 - 3.0 V	RX	30 - 60 kΩ	IHU	Received Signal Strength Indication
11	Serial TXD	Digital	3.0 V	IHU		EXP 1-4	Async, Mark High
12	IHU Audio Out	Analog	0 - 3 V (audio)	IHU	> 10 kΩ unbal.	TX	For 5 kHz deviation, 10 Hz - 7 kHz bandwidth
13	Experiment Enable 1	Digital		IHU		EXP 1-4	HIGH = Enable EXP 1
14	Not Used						
15	Experiment Enable 2	Digital		IHU		EXP 2	HIGH = Enable EXP 2
16	RX Command Data 0	Digital		IHU			(Least Significant Bit) Not Used on Fox-1A
17	Experiment Enable 3	Digital		IHU		EXP 3	HIGH = Enable EXP 3
18	RX Command Data 1	Digital		IHU			Not Used on Fox-1A
19	Experiment Enable 4	Digital		IHU		EXP 4	HIGH = Enable EXP 4
20	RX Command Data 2	Digital		IHU			HIGH = IHU off
21	Not Used						
22	RX Command Data 3	Digital		IHU		TX	(Most Significan Bit) HIGH = Inhibit Transmit
23	I²C1 SCL	Digital	Note[1]	IHU			I²C Standard, IHU Master
24	RX Command Strobe	Digital		IHU			HIGH = Command Data change
25	I²C1 SDA	Digital	Note[1]	IHU			I²C Standard, IHU Master
26	IHU RF Control	Digital		IHU		TX	HIGH = IHU Controls RF LOW = Standalone Analog Transponder
27	Not Used						
28	IHU PTT	Digital		IHU		TX	HIGH = TRANSMIT
29	Solar Safe N	Switch	N/A	BATT	N/A	PSU	N.O. for operation
30	RF TX Active	Digital		TX		IHU	HIGH = RF TX on
31	Alert Signal	Digital		IHU		BATT	
32	RX CD	Digital		RX		TX IHU	HIGH = valid receive signal
33	-Z Deploy Switch 1	Switch	N/A	TX	N/A	PSU/BATT	N.O. when deployed
34	RX Audio	Analog	0 - 3 V (audio)	RX	> 10 kΩ unbal.	IHU	10 Hz - 7 kHz bandwidth
35	-Z Deploy Switch 2	Switch	N/A	TX	N/A	PSU/BATT	N.O. when deployed
36	Not Used						
37	I²C2 SCL	Digital	Note[1]	IHU		PSU/BATT	I²C Standard, IHU Master
38	Sensor Power	Analog	+3 VDC	IHU		TX RX BATT EXP4	Power for analog telemetry sensors
39	I²C2 SDA	Digital	Note[1]	IHU		PSU/BATT	I²C Standard, IHU Master
40	TX Frequency Control	Digital		IHU		TX	Not Used on Fox-1A
41	+Z Thermistor	Analog	N/A	EXP 4	N/A	PSU	
42	RX Frequency Control	Digital		IHU		RX	Not Used on Fox-1A
43	-Z Thermistor	Analog	N/A	TX	N/A	PSU	
44	-Y Antenna Deploy	Analog	Vbatt	IHU	7 Ω resistor	PSU	
45	+Z CIC	Power	N/A	EXP 4	N/A	PSU	
46	-Y Antenna Sensor	Switch	N/A	PSU	N.O.	IHU	N.O. when deployed
47	-Z CIC	Power	N/A	TX	N/A	PSU	
48	+Y Antenna Sensor	Switch	N/A	PSU	N.O.	IHU	N.O. when deployed
49	Umbilical USBP	Digital		BATT		IHU	USB Standard
50	+Y Antenna Deploy	Analog	Vbatt	IHU	7 Ω resistor	PSU	
51	Umbilical USBM	Digital		BATT		IHU	USB Standard
52	Not Used						
53	Umbilical Power Active	Digital		BATT		IHU	HIGH = Running on Umbilical Port Power
54	Not Used						
55	Solar Power A	Power	Vbatt	PSU		BATT	
56	Solar Power B	Power	Vbatt	PSU		BATT	
57	Vbatt	Power Bus	3.3 - 4.2 VDC	BATT/PSU		ALL	
58	Vbatt	Power Bus	3.3 - 4.2 VDC	BATT/PSU		ALL	
59	Vbatt	Power Bus	3.3 - 4.2 VDC	BATT/PSU		ALL	
60	Vbatt	Power Bus	3.3 - 4.2 VDC	BATT/PSU		ALL	
	Version 2.96						
	Note[1] All SPI and I²C signals are 3.0 V levels			All Digital signals are 3.0 V CMOS logic levels high impedance load unless otherwise noted			

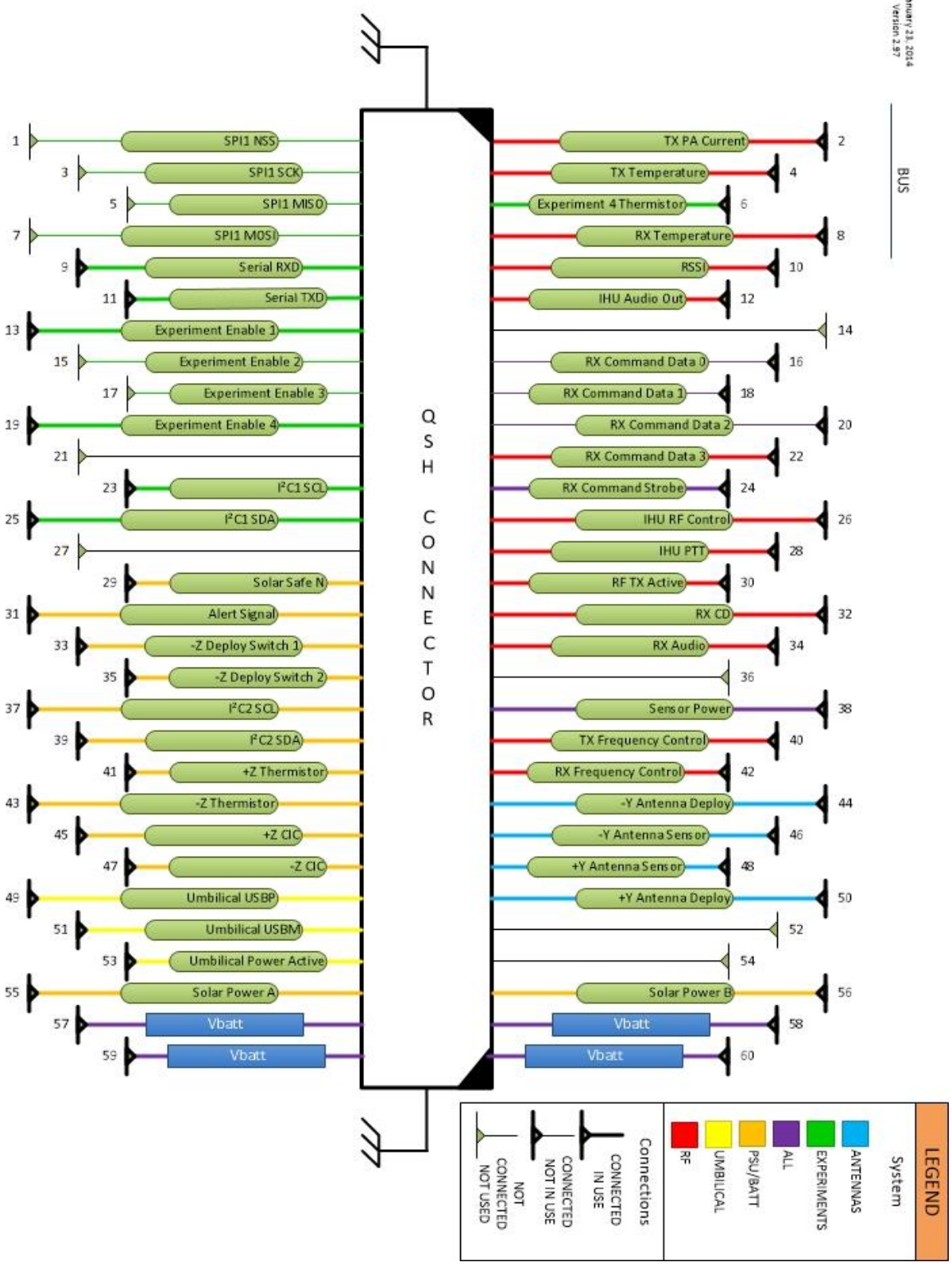

Figure 2: Complete Bus Connection Pin Assignments

3 RF Transmitter System

3.1 System Requirements Applicable to RF Transmitter System

<table>
<tr><td>2.2.1</td><td>The satellite avionics shall be designed for -40C to +70C operating temperature.</td></tr>
<tr><td>2.2.3</td><td>The satellite shall be designed to tolerate the radiation environment in orbit.</td></tr>
<tr><td>2.3.1</td><td>The satellite shall be designed for a minimum 5-year, on-orbit lifetime.</td></tr>
<tr><td>2.4.1</td><td>All RF transmitters shall meet or exceed the requirements specified in the ITU Radio Regulations, Technical Characteristics, Volume 3, article 3.</td></tr>
<tr><td>2.4.3</td><td>All satellite downlinks shall be in the 2 meter band within the amateur satellite service.</td></tr>
<tr><td>2.4.4</td><td>All satellite transmitter and receiver frequencies shall deviate by no more than 5 parts-per-million from the specified values including initial accuracy and temperature variation.</td></tr>
<tr><td>2.4.5</td><td>All satellite frequencies shall be coordinated with the IARU.</td></tr>
<tr><td>3.8.1</td><td>The satellite shall include an FM downlink transmitter.</td></tr>
<tr><td>3.8.2</td><td>The transmitter shall have specifications as shown in Table 2.
<table>
<tr><td>Power Output</td><td>400 mW (min.)</td></tr>
<tr><td>FM Deviation</td><td>5 kHz</td></tr>
<tr><td>Audio Bandwidth</td><td>3 kHz</td></tr>
</table></td></tr>
<tr><td>3.8.3</td><td>The transmitter shall provide a means to prevent over modulation.</td></tr>
<tr><td>3.9.1</td><td>The satellite shall provide an FM transponder via the RF uplink and RF downlink.</td></tr>
<tr><td>3.9.3</td><td>In Transponder Mode, the downlink transmitter shall be keyed (i.e. PTT-on) by the IHU for a minimum of 30 seconds following detection of the 67 Hz CTCSS tone.</td></tr>
<tr><td>3.9.5</td><td>In Transponder Mode, the 67 Hz CTCSS tone is not required for a received signal to be repeated on the downlink, once the transmitter has been keyed.</td></tr>
<tr><td>3.9.7</td><td>In the event of shutdown or failure of the IHU, the satellite shall default to simple carrier operated repeater operation.</td></tr>
<tr><td>3.10.1</td><td>The satellite shall collect telemetry data.</td></tr>
<tr><td>3.10.2</td><td>The telemetry data shall include at a minimum, measured parameters as shown in Table 3.
<table>
<tr><th>Parameter Name</th><th>Description</th></tr>
<tr><td>CELL V</td><td>Voltages of battery cells</td></tr>
<tr><td>PANEL V</td><td>Voltages of solar panels</td></tr>
<tr><td>TOTAL I</td><td>Total DC current out of power system</td></tr>
<tr><td>PA I</td><td>DC current into RF power amp</td></tr>
<tr><td>BATTERY T</td><td>Temperature of battery</td></tr>
<tr><td>PANEL T</td><td>Temperatures of solar panels</td></tr>
<tr><td>TX T</td><td>Temperature of RF transmitter card</td></tr>
</table></td></tr>
</table>

<table>
<tr><td></td><td><table><tr><td>RX T</td><td>Temperature of RF receiver card</td></tr></table></td></tr>
<tr><td>3.10.3</td><td>The measured parameters shall be sampled at least every 15 seconds.</td></tr>
<tr><td>3.11.1</td><td>The satellite shall send slow speed telemetry using FSK on the RF downlink.</td></tr>
<tr><td>3.11.2</td><td>The FSK shall use the frequency spectrum below the audible range.</td></tr>
<tr><td>3.11.3</td><td>The telemetry shall be transmitted simultaneously with any transponder communications.</td></tr>
<tr><td>3.12.1</td><td>The satellite shall provide the means to process commands sent via the RF uplink from a ground control station.</td></tr>
<tr><td>3.12.2</td><td>The commands received via the RF uplink shall not be repeated on the RF downlink.</td></tr>
<tr><td>3.12.3</td><td>The following commands shall be provided, as shown in Table 5.
<table>
<tr><th>Command</th><th>Operation</th></tr>
<tr><td>SAFE MODE</td><td>Enter Safe Mode</td></tr>
<tr><td>INHIBIT</td><td>Inhibit RF transmission</td></tr>
<tr><td>IHU OFF</td><td>Power off IHU & PSU</td></tr>
<tr><td>IHU ON</td><td>Power on IHU & PSU</td></tr>
<tr><td>CLEAR</td><td>Clear stored telemetry</td></tr>
<tr><td>TRANSPONDER MODE</td><td>Enter Transponder Mode</td></tr>
<tr><td>DATA MODE</td><td>Enter Data Mode</td></tr>
</table></td></tr>
<tr><td>3.12.5</td><td>An INHIBIT command shall cause the satellite to cease RF transmissions.</td></tr>
<tr><td>3.13.8</td><td>In Transponder Mode, the transponder and the slow speed telemetry shall be active.</td></tr>
<tr><td>3.13.9</td><td>In Data Mode, the high speed telemetry shall be active and the transponder shall not be active. (i.e. signals that appear on the uplink shall not be repeated on the downlink.)</td></tr>
</table>

3.2 Initial Surge Current Limits

3.2.1 The RF Transmitter design shall limit initial inrush current to 2.5 Amperes.

3.3 Volume Requirements Applicable to RF Transmitter System

3.3.1 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 5 mm from the –Z surface of the PC board.

3.3.2 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 6.0 mm from the +Z surface of the PC board.

3.4 Interface Control Documents Applicable to RF Transmitter System

AMSAT *Fox-1* IHU to RF System Interface Control Document

3.5 PCB Plating Requirements Applicable to RF Transmitter System

3.5.1 ENIG then selective flash gold four mounting pads.

3.6 RF Transmitter System PCB Bus Connections

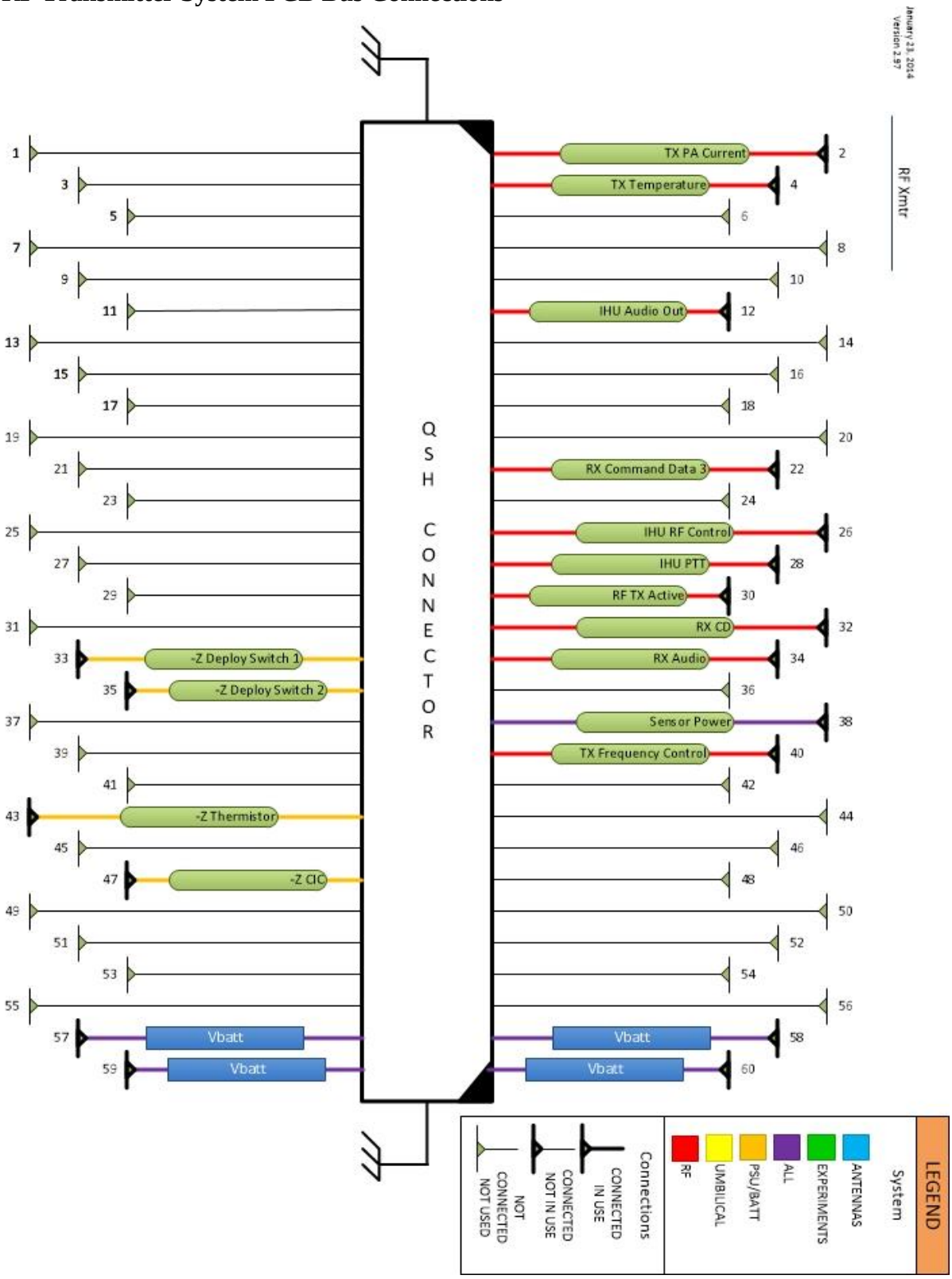

Figure 3: RF Transmitter System Bus Connection Pin Assignments

3.7 RF Transmitter System PCB External Connections

3.7.1 2 meter band RF output, coaxial cable to Transmit Antenna
3.7.2 Spacecraft deployment switches cable(s) TBR
3.7.3 Three connections via Samtec FSI-105-06-L-S-AD connector
- **3.7.3.1** 1 contact -Z Solar Panel Thermistor
- **3.7.3.2** 1 contact -Z Solar Panel CIC +
- **3.7.3.3** 1 contact common or - for above four connections

Table 2: External Connection Signal Characteristics

External Connection	Nomenclature	Type	Voltage/ Power	Source System	Load Z	Bus Pin
Coaxial Cable	2 meter Antenna ≈ 145.9 MHz	RF	0 to +30 dBm	2 meter Antenna	50 Ω unbal.	N/A

Table 3: -Z PCB face FSI-105-06-L-S-AD connector mates to pads on –Z Solar Panel

Pin	Nomenclature	Type	Voltage	Source System	Load Z	Load System	Bus Pin
1	-Z Thermistor	Analog	N/A	N/A	N/A	PSU	43
2	N/C						
3	-Z Solar Panel Common						Ground Plane
4	N/C						
5	-Z CIC	Power	N/A	N/A	N/A	PSU	47

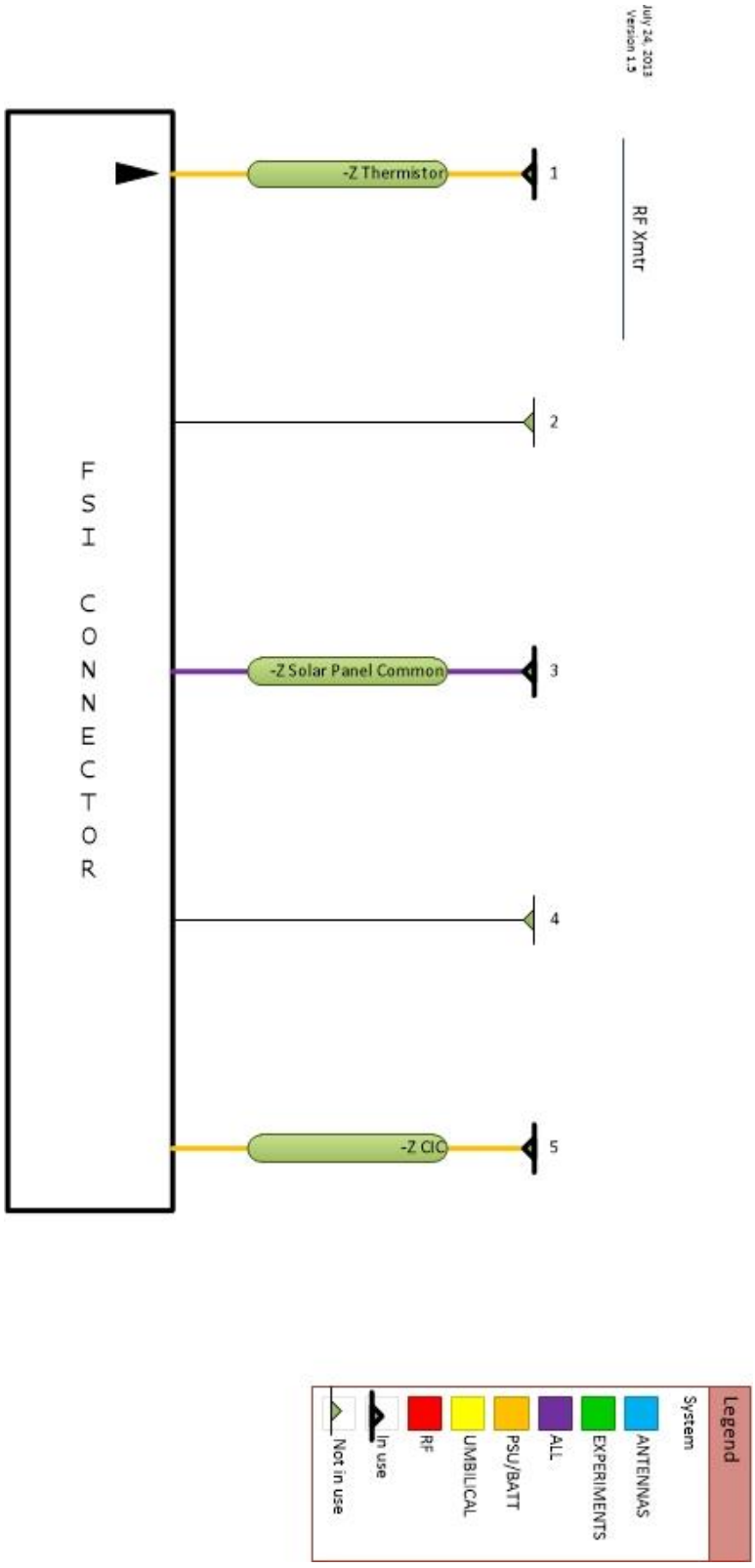

Figure 4: RF Transmitter System FSI-105-06-L-S-AD Connection Pin Assignments

4 RF Receiver System

4.1 System Requirements Applicable to RF Receiver System

<table>
<tr><td>2.2.1</td><td>The satellite avionics shall be designed for -40C to +70C operating temperature.</td></tr>
<tr><td>2.2.3</td><td>The satellite shall be designed to tolerate the radiation environment in orbit.</td></tr>
<tr><td>2.3.1</td><td>The satellite shall be designed for a minimum 5-year, on-orbit lifetime.</td></tr>
<tr><td>2.4.2</td><td>All satellite uplinks shall be in the 70 cm band of the amateur satellite service.</td></tr>
<tr><td>2.4.5</td><td>All satellite frequencies shall be coordinated with the IARU.</td></tr>
<tr><td>3.7.1</td><td>The satellite shall include an FM uplink receiver.</td></tr>
<tr><td>3.7.2</td><td>The receiver shall have specifications as shown in Table 1.
<table>
<tr><td>Sensitivity</td><td>-120 dBm for 12 dB SINAD (min.)</td></tr>
<tr><td>FM Deviation</td><td>5 kHz</td></tr>
<tr><td>Audio Bandwidth</td><td>3 kHz</td></tr>
<tr><td>Input Frequency Acceptance</td><td>Receiver shall accept signals that are off frequency by ±2.5 kHz (min.)</td></tr>
</table></td></tr>
<tr><td>3.8.3</td><td>The transmitter shall provide a means to prevent over modulation.</td></tr>
<tr><td>3.9.1</td><td>The satellite shall provide an FM transponder via the RF uplink and RF downlink.</td></tr>
<tr><td>3.9.7</td><td>In the event of shutdown or failure of the IHU, the satellite shall default to simple carrier operated repeater operation.</td></tr>
<tr><td>3.10.1</td><td>The satellite shall collect telemetry data.</td></tr>
<tr><td>3.10.2</td><td>The telemetry data shall include at a minimum, measured parameters as shown in Table 3.
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<tr><td>PANEL T</td><td>Temperatures of solar panels</td></tr>
<tr><td>TX T</td><td>Temperature of RF transmitter card</td></tr>
<tr><td>RX T</td><td>Temperature of RF receiver card</td></tr>
</table></td></tr>
<tr><td>3.10.3</td><td>The measured parameters shall be sampled at least every 15 seconds.</td></tr>
<tr><td>3.12.2</td><td>The commands received via the RF uplink shall not be repeated on the RF downlink.</td></tr>
<tr><td>3.13.12</td><td>The RF uplink shall be monitored for commands in all modes.</td></tr>
</table>

4.2 Initial Surge Current Limits

4.2.1 The RF Receiver design shall limit initial inrush current to 0.1 Amperes.

4.3 Volume Requirements Applicable to RF Receiver System

4.3.1 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 1 mm from the –Z surface of the PC board.

4.3.2 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 6.0 mm from the +Z surface of the PC board.

4.4 Interface Control Documents Applicable to RF Receiver System

AMSAT *Fox-1* IHU to RF System Interface Control Document

4.5 PCB Plating Requirements Applicable to RF Receiver System

4.5.1 ENIG then selective flash gold four mounting pads.

4.6 RF Receiver System PCB Bus Connections

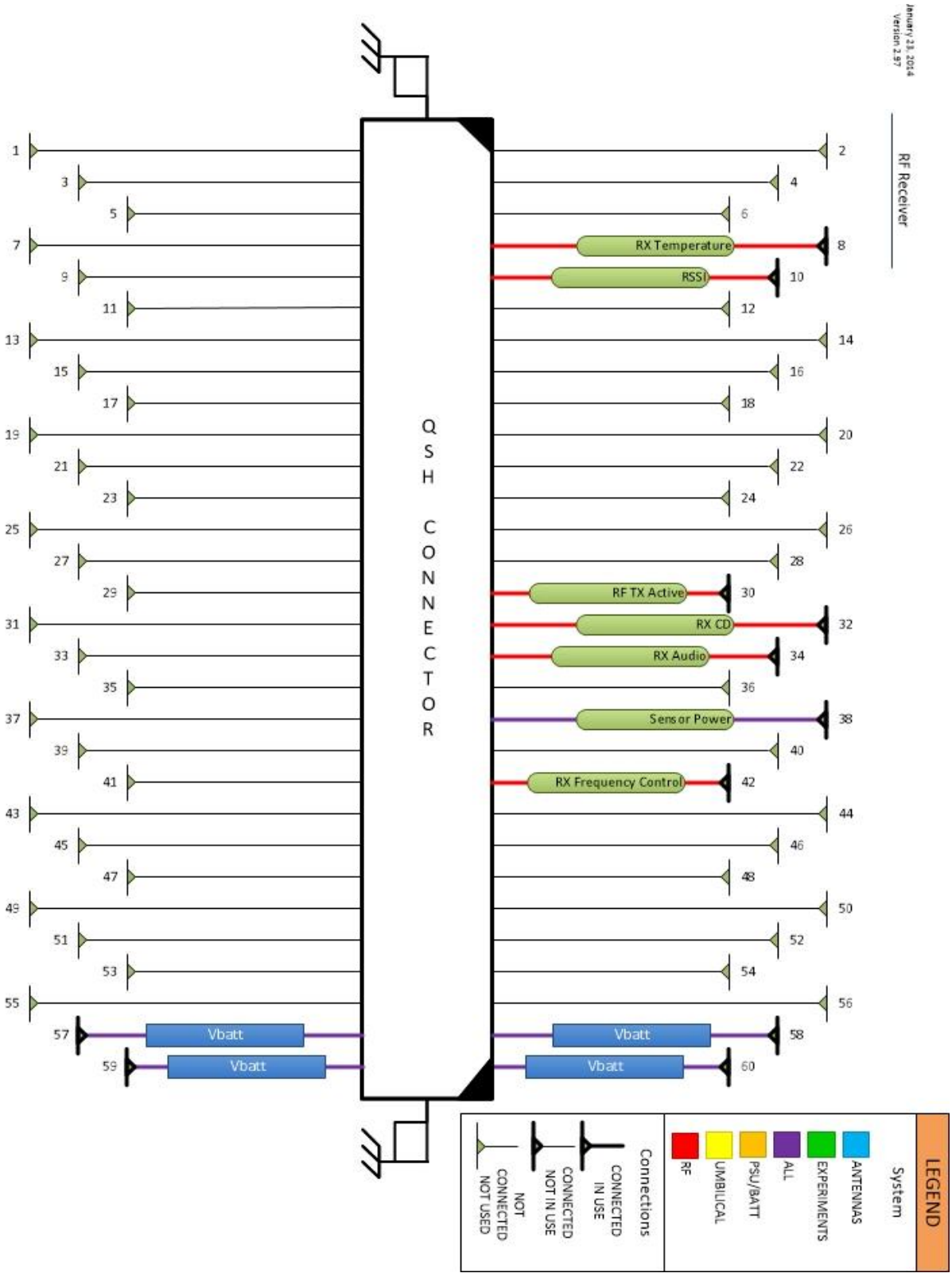


Figure 5: RF Receiver System Bus Connection Pin Assignments

4.7 RF Receiver System PCB External Connections

4.7.1 70cm band RF input, coaxial cable to Receive Antenna

Table 4: RF Receiver System External Connection Signal Characteristics

External Connection	Nomenclature	Type	Voltage/ Power	Source System	Load Z	Bus Pin
Coaxial Cable	70 cm RF Input 437 MHz	RF	-60 dBm to -140 dBm	70 cm Antenna	50 Ω unbal.	N/A

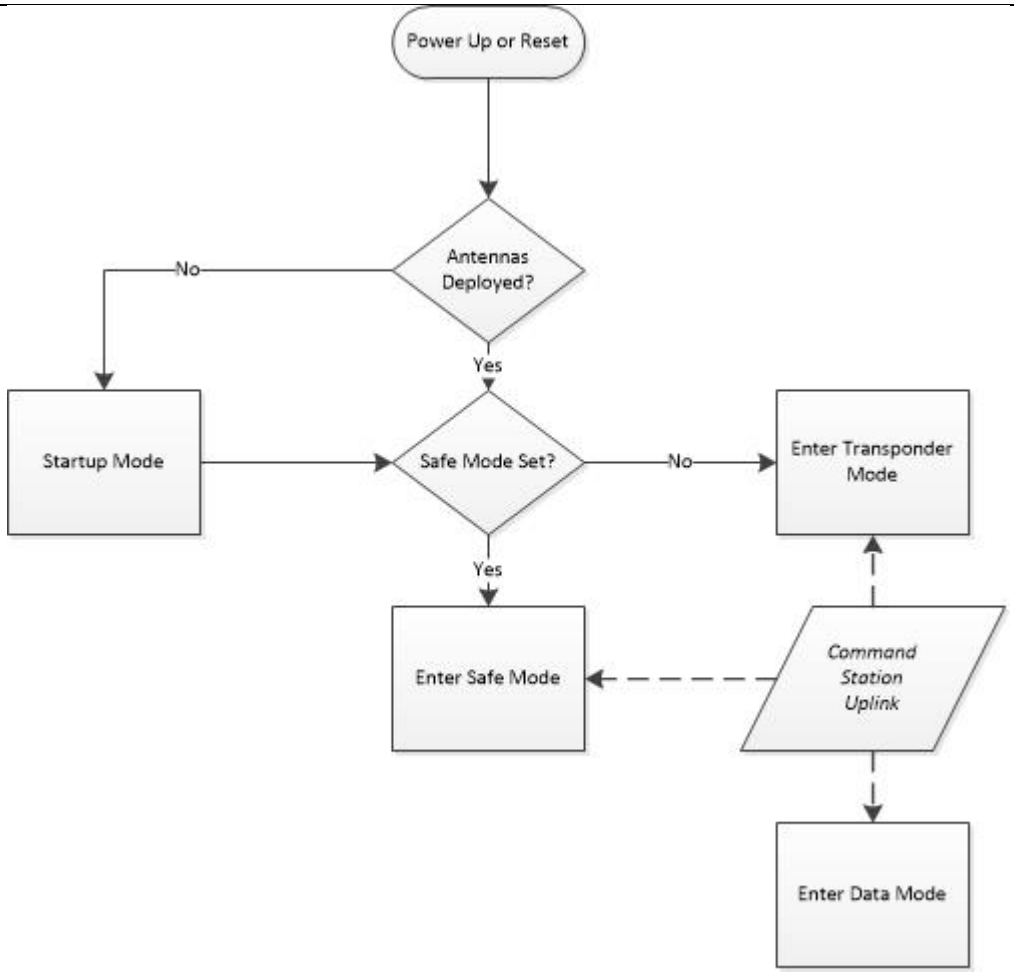
5 Internal Housekeeping Unit (IHU) System

5.1 System Requirements Applicable to Internal Housekeeping Unit (IHU) System

<table>
<tr><td>2.2.1</td><td>The satellite avionics shall be designed for -40C to +70C operating temperature.</td></tr>
<tr><td>2.2.3</td><td>The satellite shall be designed to tolerate the radiation environment in orbit.</td></tr>
<tr><td>2.3.1</td><td>The satellite shall be designed for a minimum 5-year, on-orbit lifetime.</td></tr>
<tr><td>3.3.2</td><td>The satellite shall include an umbilical port as per the CubeSat Design Specification.</td></tr>
<tr><td>3.4.3</td><td>The satellite shall provide the means to run diagnostic tests via the umbilical port while integrated with the P-POD.</td></tr>
<tr><td>3.6.2</td><td>The satellite shall provide a means to activate and deactivate the experiment payloads.</td></tr>
<tr><td>3.6.3</td><td>The satellite shall provide a means to telemeter data from the experiment payloads.</td></tr>
<tr><td>3.9.2</td><td>In Transponder Mode, the IHU shall detect the presence of a 67 Hz CTCSS tone on the uplink.</td></tr>
<tr><td>3.9.3</td><td>In Transponder Mode, the downlink transmitter shall be keyed (i.e. PTT-on) by the IHU for a minimum of 30 seconds following detection of the 67 Hz CTCSS tone.</td></tr>
<tr><td>3.9.4</td><td>In Transponder Mode, the downlink transmitter shall stay on continuously as long as the 67 Hz CTCSS tone is detected at least once during the period the transmitter is being keyed (i.e. PTT-on).</td></tr>
<tr><td>3.9.5</td><td>In Transponder Mode, the 67 Hz CTCSS tone is not required for a received signal to be repeated on the downlink, once the transmitter has been keyed.</td></tr>
<tr><td>3.9.6</td><td>In Transponder Mode, if the downlink transmitter has been un-keyed for a period of 2 minutes, the satellite shall send "HI THIS IS AMATEUR RADIO SATELLITE FOX 1" as a voice announcement on the downlink transmitter.</td></tr>
<tr><td>3.9.7</td><td>In the event of shutdown or failure of the IHU, the satellite shall default to simple carrier operated repeater operation.</td></tr>
<tr><td>3.10.1</td><td>The satellite shall collect telemetry data.</td></tr>
<tr><td>3.10.2</td><td>The telemetry data shall include at a minimum, measured parameters as shown in Table 3.
<table>
<tr><th>Parameter Name</th><th>Description</th></tr>
<tr><td>CELL V</td><td>Voltages of battery cells</td></tr>
<tr><td>PANEL V</td><td>Voltages of solar panels</td></tr>
<tr><td>TOTAL I</td><td>Total DC current out of power system</td></tr>
<tr><td>PA I</td><td>DC current into RF power amp</td></tr>
<tr><td>BATTERY T</td><td>Temperature of battery</td></tr>
<tr><td>PANEL T</td><td>Temperatures of solar panels</td></tr>
<tr><td>TX T</td><td>Temperature of RF transmitter card</td></tr>
<tr><td>RX T</td><td>Temperature of RF receiver card</td></tr>
</table></td></tr>
<tr><td>3.10.3</td><td>The measured parameters shall be sampled at least every 15 seconds.</td></tr>
<tr><td>3.10.4</td><td>The minimum and maximum values of each of the measured parameters shall be saved in non-</td></tr>
</table>

<table>
<tr><td></td><td>volatile memory.</td></tr>
<tr><td>3.10.5</td><td>The telemetry data shall also include at a minimum, calculated parameters as shown in Table 4.
<table>
<tr><th>Parameter Name</th><th>Description</th></tr>
<tr><td>UP TIME</td><td>Total seconds since avionics power-up or reset</td></tr>
<tr><td>SPIN</td><td>Satellite spin rate and direction</td></tr>
</table></td></tr>
<tr><td>3.10.6</td><td>A telemetry frame shall include the current measured values, the saved minimum and maximum values, and the current calculated values.</td></tr>
<tr><td>3.11.1</td><td>The satellite shall send slow speed telemetry using FSK on the RF downlink.</td></tr>
<tr><td>3.11.2</td><td>The FSK shall use the frequency spectrum below the audible range.</td></tr>
<tr><td>3.11.3</td><td>The telemetry shall be transmitted simultaneously with any transponder communications.</td></tr>
<tr><td>3.11.4</td><td>The telemetry transmission shall include telemetry frames.</td></tr>
<tr><td>3.11.5</td><td>The telemetry transmission shall include experiment data.</td></tr>
<tr><td>3.12.1</td><td>The satellite shall provide the means to process commands sent via the RF uplink from a ground control station.</td></tr>
<tr><td>3.12.3</td><td>The following commands shall be provided, as shown in Table 5.
<table>
<tr><th>Command</th><th>Operation</th></tr>
<tr><td>SAFE MODE</td><td>Enter Safe Mode</td></tr>
<tr><td>INHIBIT TX</td><td>Inhibit RF transmission</td></tr>
<tr><td>ENABLE TX</td><td>Enable RF transmission</td></tr>
<tr><td>IHU OFF</td><td>Power off IHU</td></tr>
<tr><td>IHU ON</td><td>Power on IHU</td></tr>
<tr><td>CLEAR</td><td>Clear stored telemetry</td></tr>
<tr><td>TRANSPONDER MODE</td><td>Enter Transponder Mode</td></tr>
<tr><td>DATA MODE</td><td>Enter Data Mode</td></tr>
<tr><td>ENABLE AUTO-SAFE</td><td>Enable Auto-Safe Mode</td></tr>
<tr><td>DISABLE AUTO-SAFE</td><td>Disable Auto-Safe Mode</td></tr>
</table></td></tr>
<tr><td>3.12.4</td><td>A SAFE MODE command shall cause the satellite to enter the Safe Mode.</td></tr>
<tr><td>3.12.5</td><td>An INHIBIT TX command shall disable the RF transmitter.</td></tr>
<tr><td>3.12.6</td><td>An ENABLE TX command shall enable the RF transmitter.</td></tr>
<tr><td>3.12.7</td><td>An IHU OFF command shall cause the IHU System to power off.</td></tr>
<tr><td>3.12.8</td><td>An IHU ON command shall cause the IHU System to power on.</td></tr>
<tr><td>3.12.9</td><td>A CLEAR command shall cause the satellite to clear the saved minimum and maximum telemetry parameter values.</td></tr>
<tr><td>3.12.10</td><td>A TRANSPONDER MODE command shall cause the satellite to enter the Transponder Mode.</td></tr>
</table>

<table>
<tr><td>3.12.11</td><td>A DATA MODE command shall cause the satellite to enter the Data Mode.</td></tr>
<tr><td>3.12.12</td><td>An ENABLE AUTO-SAFE command shall enable the auto-safe mode state.</td></tr>
<tr><td>3.12.13</td><td>A DISABLE AUTO-SAFE command shall disable the auto-safe mode state.</td></tr>
<tr><td>3.13.1</td><td>The satellite shall provide on-orbit operating modes as shown in Table 6.
<table>
<tr><th>Name</th><th>Description</th></tr>
<tr><td>Startup Mode</td><td>Wait 45 minutes and deploy antennas</td></tr>
<tr><td>Safe Mode</td><td>Wait 120 seconds then begin 10 second beacon sequence</td></tr>
<tr><td>Transponder Mode</td><td>FM transponder; PTT and low speed telemetry via IHU</td></tr>
<tr><td>Data Mode</td><td>FM transmitter; PTT and high speed telemetry via IHU</td></tr>
</table></td></tr>
<tr><td>3.13.2</td><td>The satellite shall transition between modes as shown in Figure 1.</td></tr>
<tr><td>3.13.3</td><td>Upon power-up of the avionics, the satellite shall begin operation from the "Power-up" state as shown in Figure 1.</td></tr>
<tr><td>3.13.4</td><td>An IHU ON Command shall cause the satellite to begin operation from the "Power-up" state as shown in Figure 1.</td></tr>
</table>

	
3.13.5	If the antennas have been deployed, the satellite shall determine whether the last state was Safe Mode.
3.13.5.1	If the last state was Safe Mode the satellite shall enter Safe Mode
3.13.5.2	If the last state was not Safe Mode the satellite shall enter Transponder Mode.
3.13.6	If the antennas have not been deployed, the satellite shall enter the Startup Mode.
3.13.7	In Startup Mode, the satellite shall wait 50 minutes, then deploy the antennas.
3.13.7.1	During the 50 minute wait the IHU shall flash a red LED.
3.13.7.2	During the 50 minute wait the IHU shall sound a 1 kHz beeping tone.
3.13.7.3	After the antennas have been deployed the satellite shall enter Safe Mode.
3.13.8	In Transponder Mode, the transponder and the slow speed telemetry shall be active.
3.13.9	In Data Mode, the high speed telemetry shall be active and the transponder shall not be active. (i.e. signals that appear on the uplink shall not be repeated on the downlink.)
3.13.10	If another Data Mode command is not received, the satellite shall automatically enter Transponder Mode 30 minutes after having entered Data Mode.
3.13.11	In Safe Mode the satellite shall wait 120 seconds then transmit a 10 second beacon.
3.13.11.1	The 120 second wait and 10 second beacon cycle will be repeated as long as the satellite is in Safe Mode.
3.13.12	The RF uplink shall be monitored for commands in all modes.

5.3 Initial Surge Current Limits

5.3.1 The IHU design shall limit initial inrush current to 0.1 Amperes.

5.4 Volume Requirements Applicable to IHU System

5.4.1 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 1 mm from the –Z surface of the PC board.

5.4.2 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 6.0 mm from the +Z surface of the PC board.

5.5 Interface Control Documents Applicable to IHU System

AMSAT *Fox-1* IHU to RF System Interface Control Document
AMSAT *Fox-1* IHU to PSU Interface Control Document
AMSAT *Fox-1* IHU to Battery Interface Control Document
AMSAT *Fox-1* IHU to Attitude Determination Experiment Interface Control Document
AMSAT *Fox-1* IHU to Experiment 1 Interface Control Document
AMSAT *Fox-1* IHU to Experiment 4 Interface Control Document

5.6 PCB Plating Requirements Applicable to IHU System

5.6.1 ENIG then selective flash gold four mounting pads.

5.7 Internal Housekeeping Unit (IHU) System PCB Bus Connections

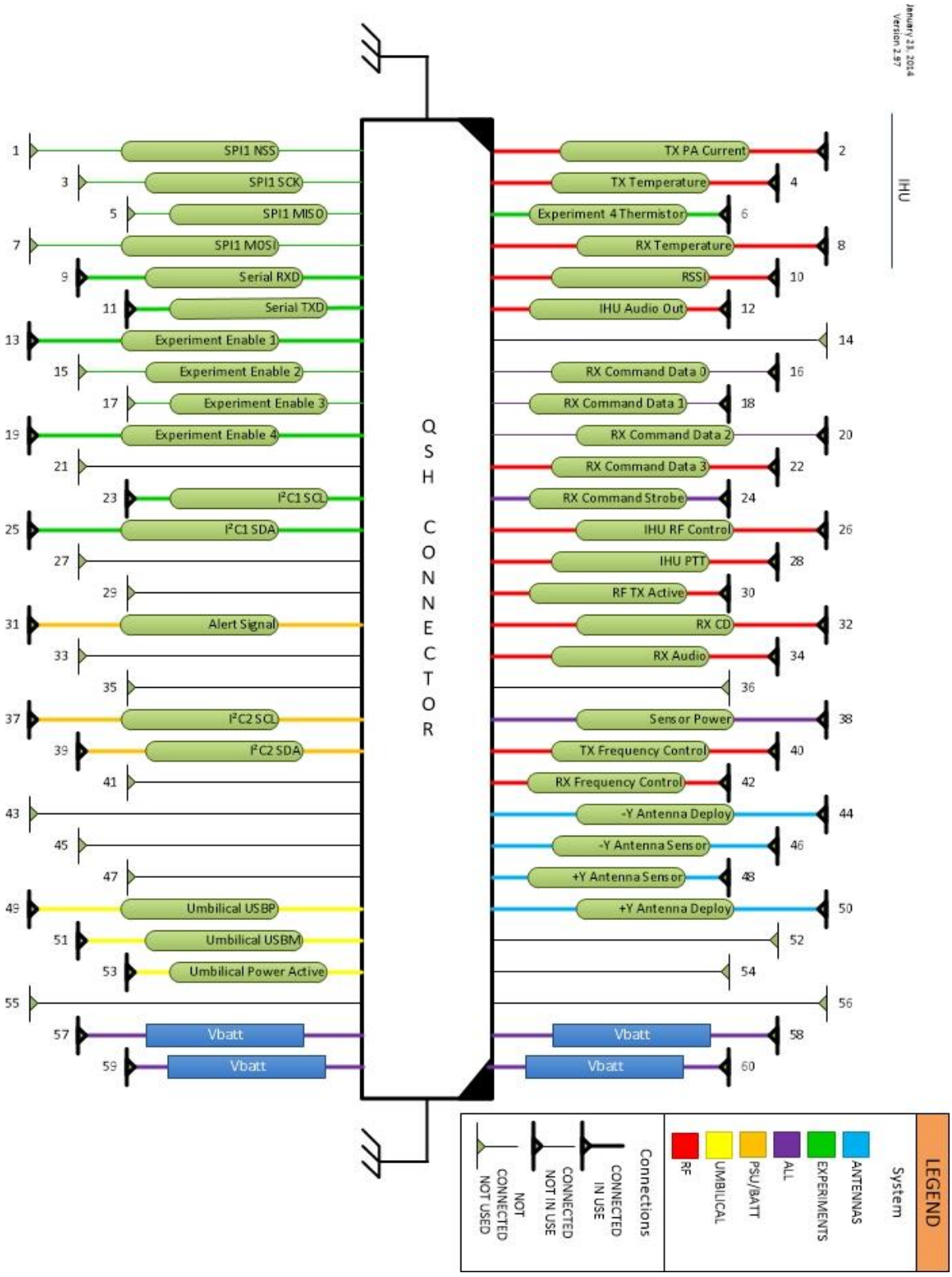


Figure 6: IHU System Bus Connection Pin Assignments

6 Power Supply System (PSU)

6.1 System Requirements Applicable to Power Supply System (PSU)

<table>
<tr><td>2.2.1</td><td>The satellite avionics shall be designed for -40C to +70C operating temperature.</td></tr>
<tr><td>2.2.3</td><td>The satellite shall be designed to tolerate the radiation environment in orbit.</td></tr>
<tr><td>2.3.1</td><td>The satellite shall be designed for a minimum 5-year, on-orbit lifetime.</td></tr>
<tr><td>3.3.1</td><td>The satellite shall include a "Remove Before Flight" pin as per the CubeSat Design Specification.</td></tr>
<tr><td>3.4.1</td><td>The satellite battery and photovoltaic panels shall be electronically disconnected from the avionics when the "Remove Before Flight" pin is inserted, regardless of the state of the deployment switch(es).</td></tr>
<tr><td>3.4.2</td><td>The satellite shall provide the means to charge the battery via the umbilical port while integrated with the P-POD.</td></tr>
<tr><td>3.5.1</td><td>The satellite shall produce electrical power from sunlight.</td></tr>
<tr><td>3.5.2</td><td>The satellite shall produce electrical power while in sunlight regardless of orientation and while tumbling or spinning.</td></tr>
<tr><td>3.5.3</td><td>The satellite shall produce sufficient average electrical power to operate continuously in the orbit of maximum eclipse.</td></tr>
<tr><td>3.5.4</td><td>The satellite shall provide sufficient battery capacity to operate continuously in the orbit of maximum eclipse.</td></tr>
<tr><td>3.6.1</td><td>The satellite shall provide DC power for experiment payloads.</td></tr>
<tr><td>3.10.1</td><td>The satellite shall collect telemetry data.</td></tr>
<tr><td>3.10.2</td><td>The telemetry data shall include at a minimum, measured parameters as shown in Table 3.
<table>
<tr><th>Parameter Name</th><th>Description</th></tr>
<tr><td>CELL V</td><td>Voltages of battery cells</td></tr>
<tr><td>PANEL V</td><td>Voltages of solar panels</td></tr>
<tr><td>TOTAL I</td><td>Total DC current out of power system</td></tr>
<tr><td>PA I</td><td>DC current into RF power amp</td></tr>
<tr><td>BATTERY T</td><td>Temperature of battery</td></tr>
<tr><td>PANEL T</td><td>Temperatures of solar panels</td></tr>
<tr><td>TX T</td><td>Temperature of RF transmitter card</td></tr>
<tr><td>RX T</td><td>Temperature of RF receiver card</td></tr>
</table></td></tr>
<tr><td>3.10.3</td><td>The measured parameters shall be sampled at least every 15 seconds.</td></tr>
<tr><td>3.13.7.1</td><td>During the 45 minute wait the IHU shall flash a red LED.</td></tr>
</table>

6.2 Initial Surge Current Limits

6.2.1 The PSU design shall limit initial inrush current to 0.1 Amperes.

6.3 Volume Requirements Applicable to PSU System

6.3.1 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 1 mm from the –Z surface of the PC board.

6.3.2 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 3.0 mm from the +Z surface of the PC board within the area 0 to 4.0 mm from the +Y and +X edges of the board, and 6.0 mm from the +Z surface of the PC board in the rest of the board area.

6.4 Interface Control Documents Applicable to PSU System

AMSAT *Fox-1* IHU to PSU Interface Control Document

6.5 PCB Plating Requirements Applicable to PSU System

6.5.1 ENIG then selective flash hard gold 30 micro-inch four mounting pads and four edge fingers.

6.6 Power Supply System (PSU) PCB Bus Connections

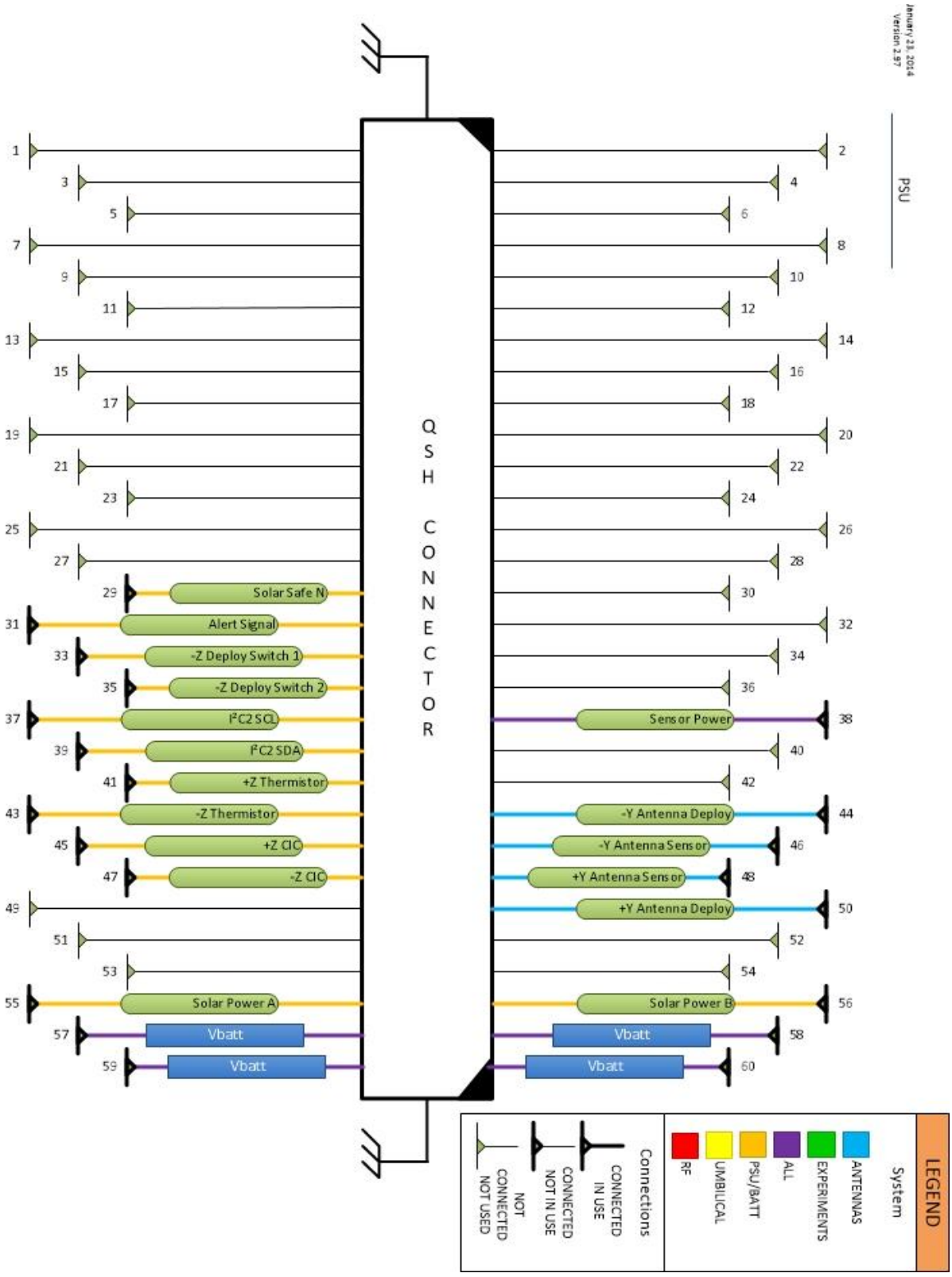


Figure 7: PSU Bus Connection Pin Assignments

6.7 Power Supply System (PSU) PCB External Connections

6.7.1 Three connections to +X Solar Panel using Samtec MEC1-105-02-L-D-NP-A connector
- **6.7.1.1** 1 contact +X Solar Panel Thermistor
- **6.7.1.2** 1 contact +X Solar Panel CIC +
- **6.7.1.3** 1 contact common or - for above two connections

6.7.2 Three connections to -X Solar Panel using Samtec MEC1-105-02-L-D-NP-A connector
- **6.7.2.1** 1 contact -X Solar Panel Thermistor
- **6.7.2.2** 1 contact -X Solar Panel CIC +
- **6.7.2.3** 1 contact common or - for above two connections

6.7.3 Five connections to +Y Solar Panel using Samtec MEC1-105-02-L-D-NP-A connector
- **6.7.3.1** 1 contact +Y Solar Panel Thermistor
- **6.7.3.2** 1 contact +Y Solar Panel CIC +
- **6.7.3.3** 1 contact TX Antenna Deploy
- **6.7.3.4** 1 contact TX Antenna Sensor
- **6.7.3.5** 1 contact common or - for above connections

6.7.4 Five connections to -Y Solar Panel using Samtec MEC1-105-02-L-D-NP-A connector
- **6.7.4.1** 1 contact -Y Solar Panel Thermistor
- **6.7.4.2** 1 contact -Y Solar Panel CIC +
- **6.7.4.3** 1 contact RX Antenna Deploy
- **6.7.4.4** 1 contact RX Antenna Sensor
- **6.7.4.5** 1 contact common or - for above connections

6.7.5 All PCB edges that connect to solar panel MEC1-105-02-L-D-NP-A connectors shall have contact pads on the PCB for all connector pins, whether connected to a trace or not.

Table 5: +X PCB edge mates to MEC1-105-02-L-D-NP-A connector on +X Solar Panel

Pin	Nomenclature	Type	Voltage	Source System	Load Z	Bus Pin
1	N/C					
2	+X Solar Panel Thermistor	Analog	N/A	N/A	N/A	N/A
3	N/C					
4	N/C					
5	N/C					
6	+X Solar Panel Common					Ground Plane
7	N/C					
8	N/C					
9	N/C					
10	+X Solar Panel CIC (+)	Power	N/A	N/A	N/A	N/A

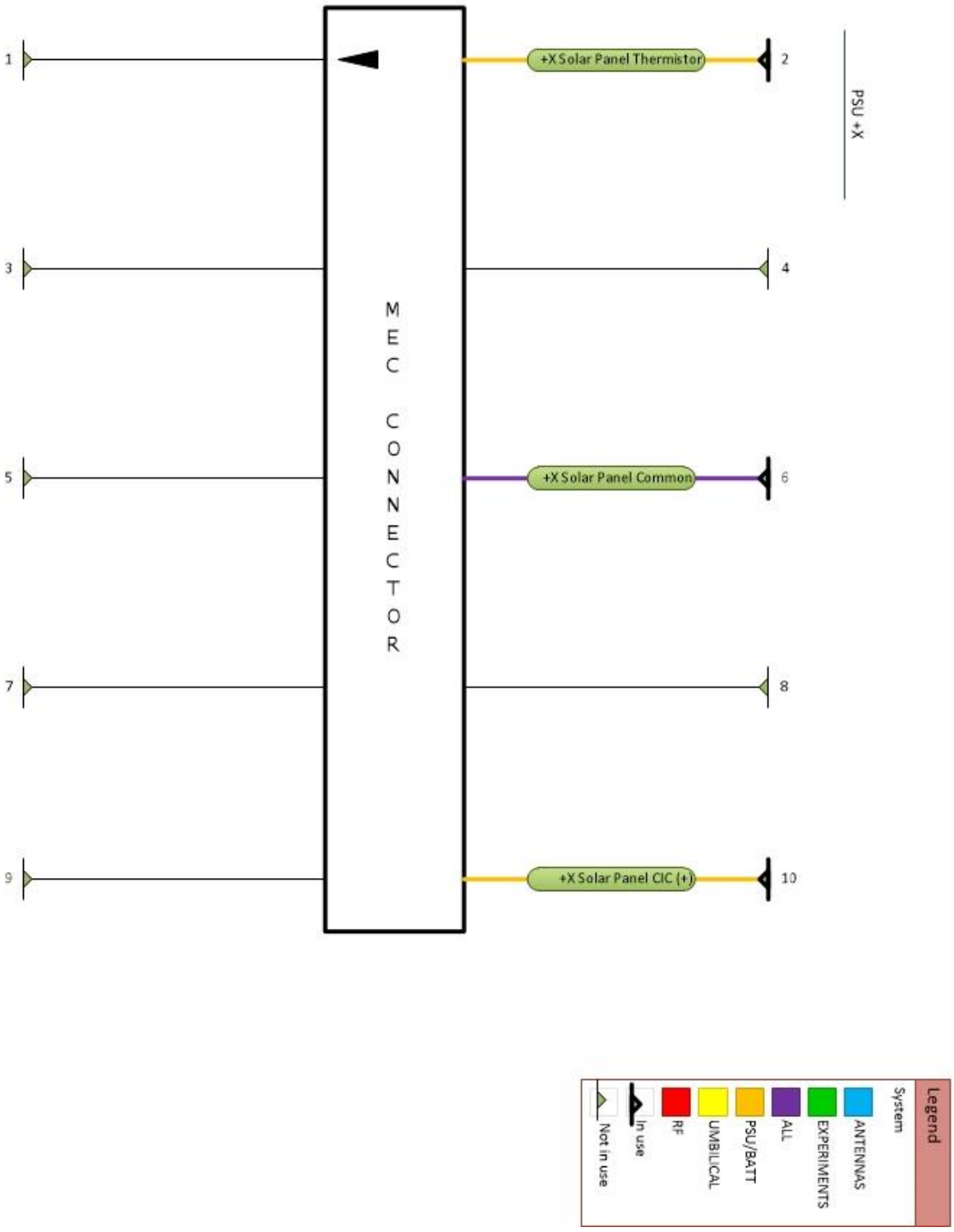


Figure 8: PSU System +X Edge MEC1-105-02-L-D-NP-A Connection Pin Assignments

Table 6: -X PCB edge mates to MEC1-105-02-L-D-NP-A connector on -X Solar Panel

Pin	Nomenclature	Type	Voltage	Source System	Load Z	Bus Pin
1	N/C					
2	-X Solar Panel Thermistor	Analog	N/A	N/A	N/A	N/A
3	N/C					
4	N/C					
5	N/C					
6	-X Solar Panel Common					Ground Plane
7	N/C					
8	N/C					
9	N/C					
10	-X Solar Panel CIC (+)	Power	N/A	N/A	N/A	N/A

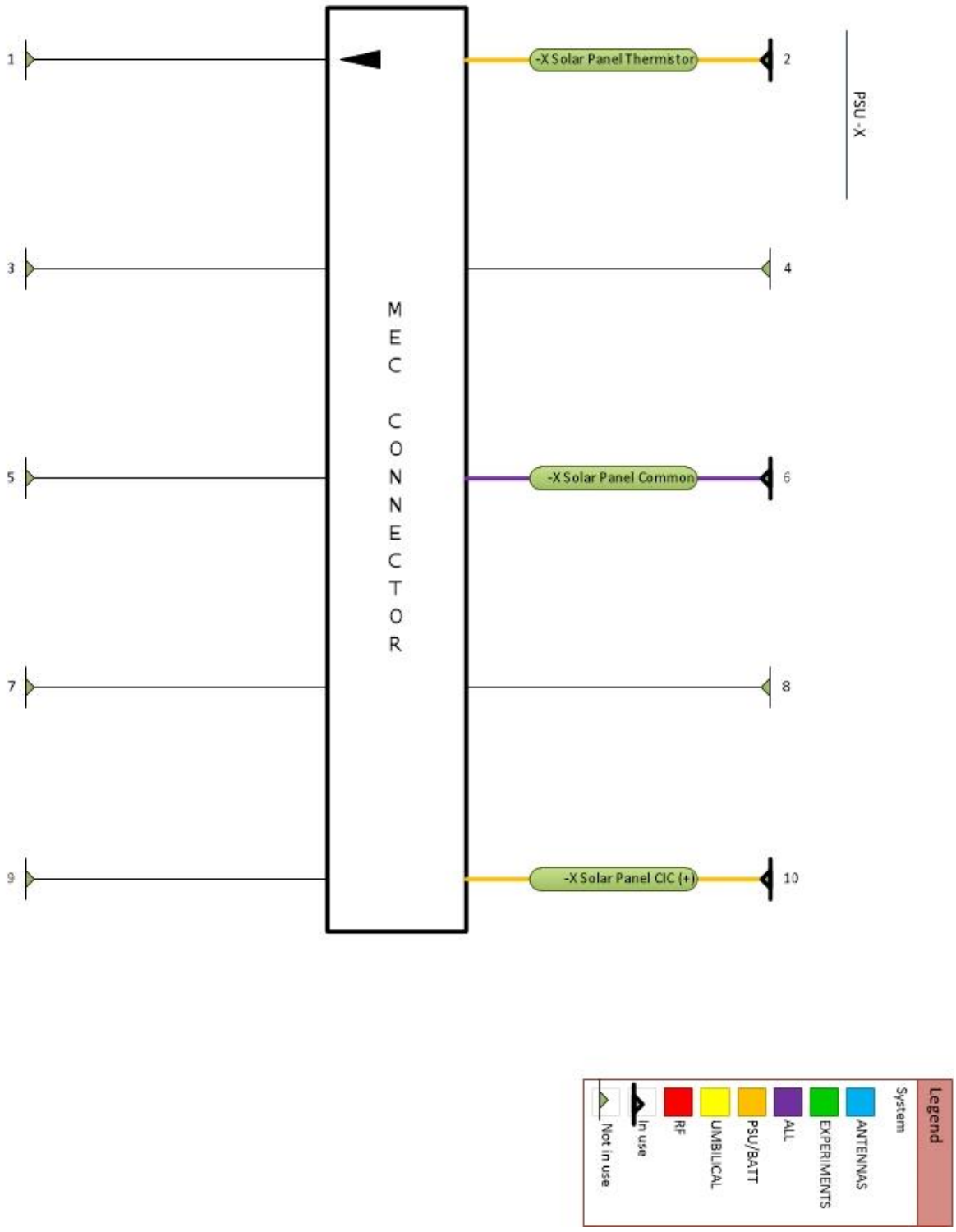


Figure 9: PSU System -X Edge MEC1-105-02-L-D-NP-A Connection Pin Assignments

Table 7: +Y PCB edge mates to MEC1-105-02-L-D-NP-A connector on +Y Solar Panel

Pin	Nomenclature	Type	Voltage	Source System	Load Z	Bus Pin
1	N/C					
2	+Y Solar Panel Thermistor	Analog	N/A	N/A	N/A	N/A
3	N/C					
4	+Y Antenna Sensor	Switch	N/A	PSU	N.O.	48
5	N/C					
6	+Y Solar Panel Common					Ground Plane
7	N/C					
8	+Y Antenna Deploy	Analog	Vbatt	IHU	7 Ω resistor	50
9	N/C					
10	+Y Solar Panel CIC (+)	Power	N/A	N/A	N/A	N/A

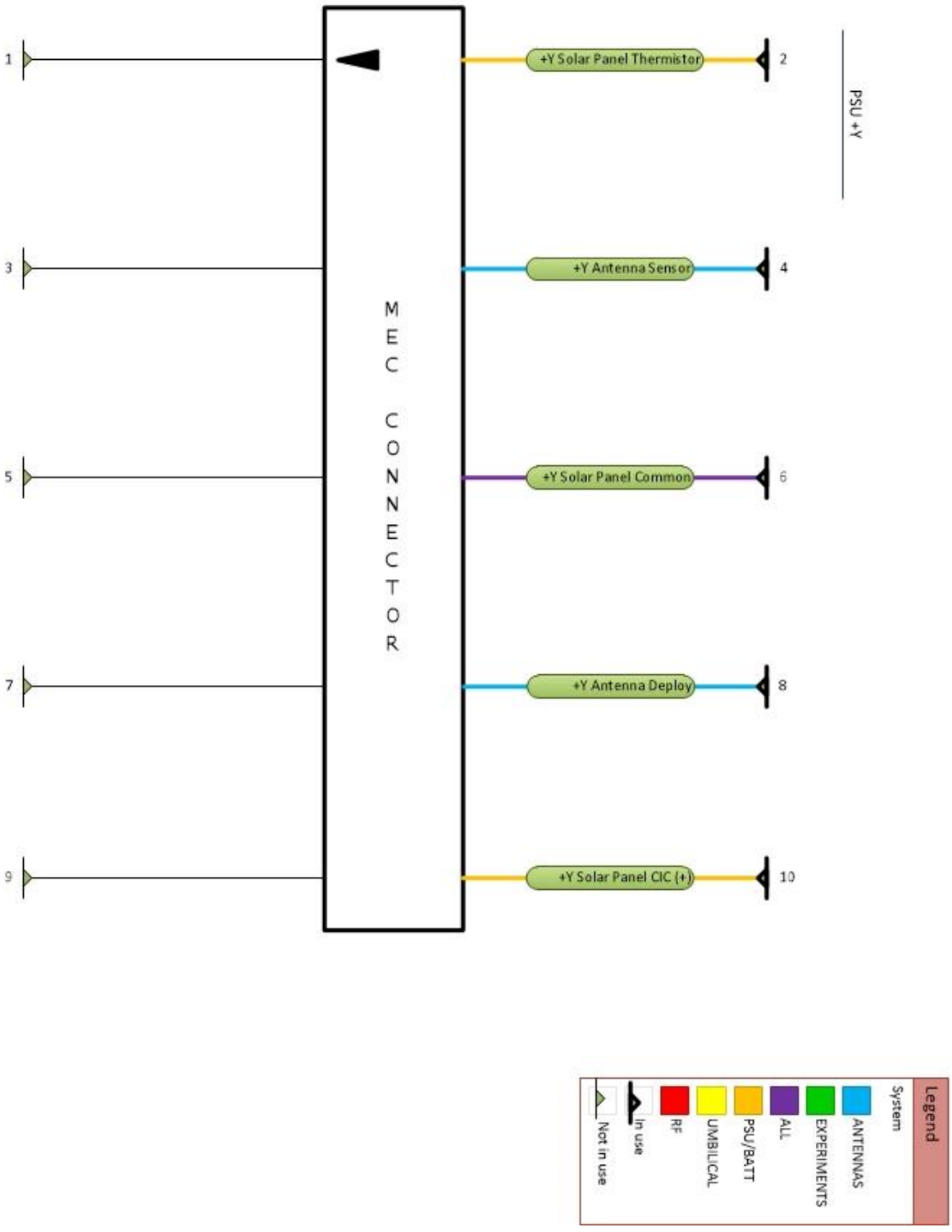


Figure 10: PSU System +Y Edge MEC1-105-02-L-D-NP-A Connection Pin Assignments

Table 8: -Y PCB edge mates to MEC1-105-02-L-D-NP-A connector on -Y Solar Panel

Pin	Nomenclature	Type	Voltage	Source System	Load Z	Bus Pin
1	N/C					
2	-Y Solar Panel Thermistor	Analog	N/A	N/A	N/A	N/A
3	N/C					
4	-Y Antenna Sensor	Switch	N/A	PSU	N.O.	46
5	N/C					
6	-Y Solar Panel Common					Ground Plane
7	N/C					
8	-Y Antenna Deploy	Analog	Vbatt	IHU	7 Ω resistor	44
9	N/C					
10	-Y Solar Panel CIC (+)	Power	N/A	N/A	N/A	N/A

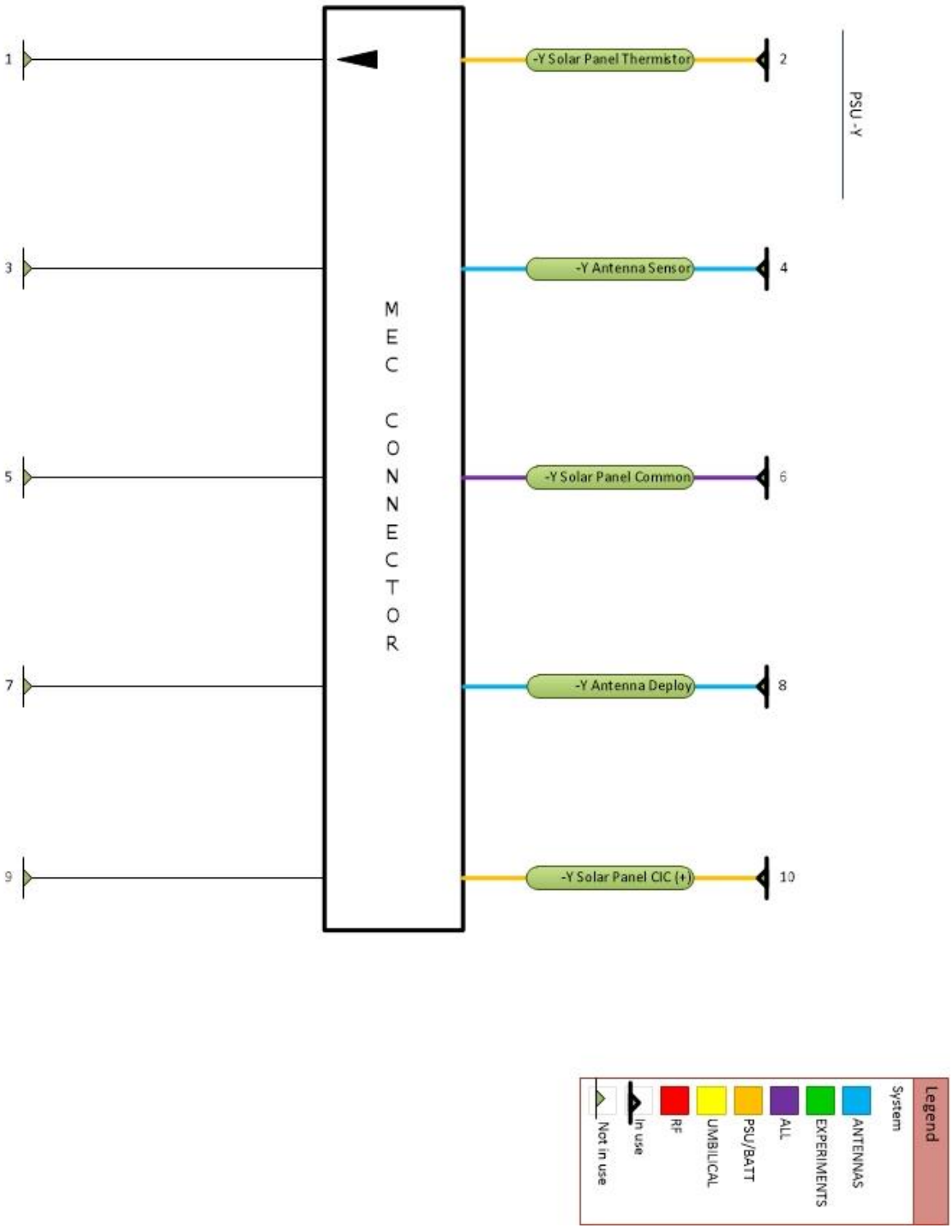


Figure 11: PSU System -Y Edge MEC1-105-02-L-D-NP-A Connection Pin Assignments

7 Battery System

7.1 System Requirements Applicable to Battery PCB 1 System (BATT1)

<table>
<tr><td>2.2.1</td><td>The satellite avionics shall be designed for -40C to +70C operating temperature.</td></tr>
<tr><td>2.2.3</td><td>The satellite shall be designed to tolerate the radiation environment in orbit.</td></tr>
<tr><td>2.3.1</td><td>The satellite shall be designed for a minimum 5-year, on-orbit lifetime.</td></tr>
<tr><td>3.3.1</td><td>The satellite shall include a "Remove Before Flight" pin as per the CubeSat Design Specification.</td></tr>
<tr><td>3.4.1</td><td>The satellite battery and photovoltaic panels shall be electronically disconnected from the avionics when the "Remove Before Flight" pin is inserted, regardless of the state of the deployment switch(es).</td></tr>
<tr><td>3.4.2</td><td>The satellite shall provide the means to charge the battery via the umbilical port while integrated with the P-POD.</td></tr>
<tr><td>3.5.3</td><td>The satellite shall produce sufficient average electrical power to operate continuously in the orbit of maximum eclipse.</td></tr>
<tr><td>3.5.4</td><td>The satellite shall provide sufficient battery capacity to operate continuously in the orbit of maximum eclipse.</td></tr>
<tr><td>3.10.1</td><td>The satellite shall collect telemetry data.</td></tr>
<tr><td>3.10.2</td><td>The telemetry data shall include at a minimum, measured parameters as shown in Table 3.
<table>
<tr><th>Parameter Name</th><th>Description</th></tr>
<tr><td>CELL V</td><td>Voltages of battery cells</td></tr>
<tr><td>PANEL V</td><td>Voltages of solar panels</td></tr>
<tr><td>TOTAL I</td><td>Total DC current out of power system</td></tr>
<tr><td>PA I</td><td>DC current into RF power amp</td></tr>
<tr><td>BATTERY T</td><td>Temperature of battery</td></tr>
<tr><td>PANEL T</td><td>Temperatures of solar panels</td></tr>
<tr><td>TX T</td><td>Temperature of RF transmitter card</td></tr>
<tr><td>RX T</td><td>Temperature of RF receiver card</td></tr>
</table></td></tr>
<tr><td>3.10.3</td><td>The measured parameters shall be sampled at least every 15 seconds.</td></tr>
</table>

7.2 Volume Requirements Applicable to Battery PCB 1 System

7.2.1 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 4.0 mm from the -Z surface of the PC board within the area 0 to 4.0 mm from the +Y and +X edges of the board, and 1.0 mm from the -Z surface of the PC board in the rest of the board area.

7.2.2 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 17.0 mm from the +Z surface of the PC board.

7.3 Interface Control Documents Applicable to Battery PCB 1 System

AMSAT *Fox-1* IHU to Battery Interface Control Document

7.4 PCB Plating Requirements Applicable to Battery PCB 1 System

7.4.1 ENIG then selective flash gold four mounting pads.

7.5 Battery PCB 1 System Bus Connections

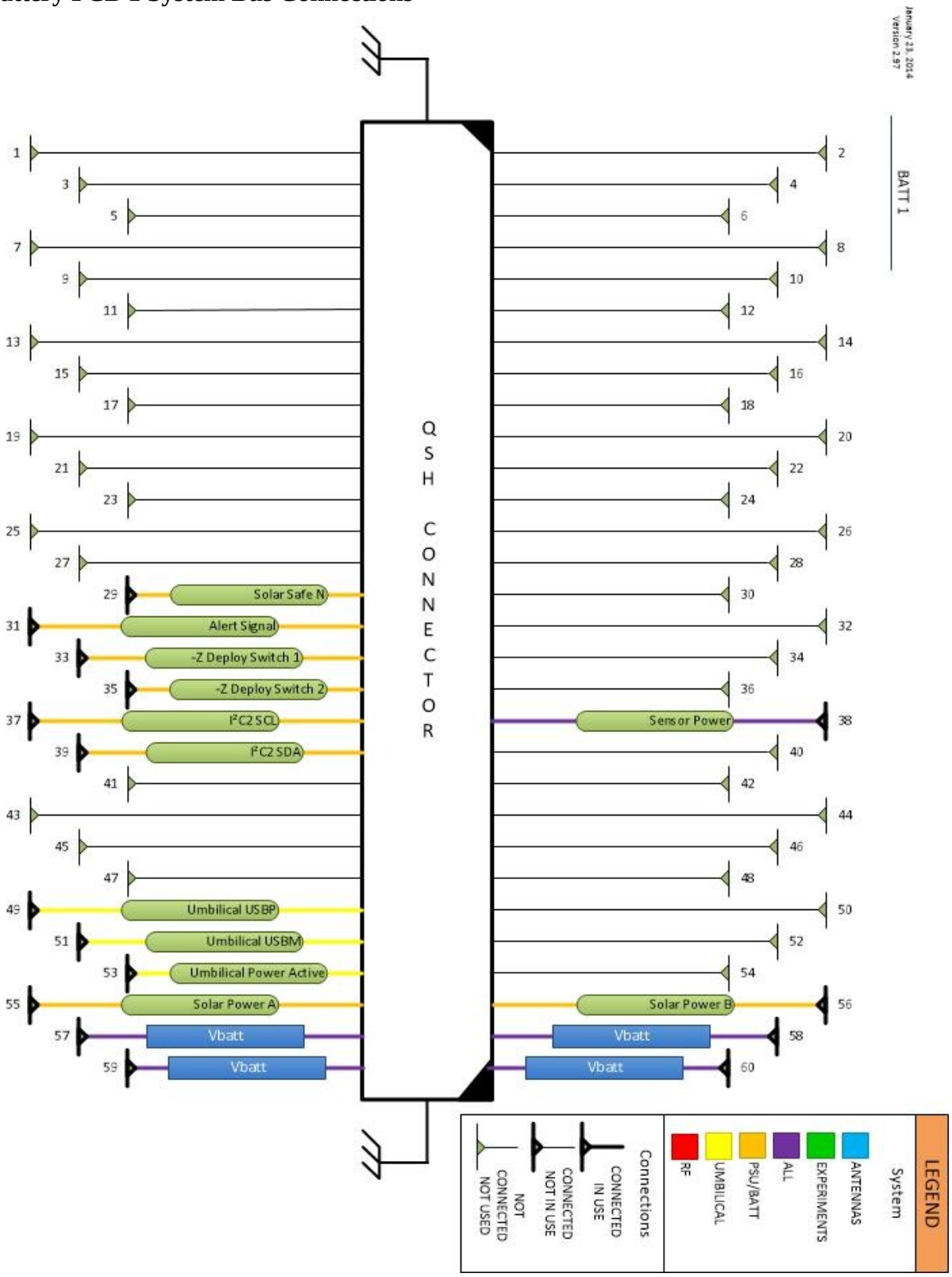


Figure 12: Battery 1 System Bus Connection Pin Assignments

7.6 Battery PCB 1 System External Connections

7.6.1 Umbilical as USB mini type B receptacle
7.6.2 Remove Before Flight as 3.5mm normally open TS jack

Table 9: Battery 1 External Connection Signal Characteristics

External Connection	Nomenclature	Type	Voltage/ Power	Source System	Load Z	Bus Pin
USB 1	USB +5 VDC	Analog	5 VDC	USB CONNECTOR	N/A	N/A
USB 2	USB Data - (USBM)	Digital	3.0 V CMOS logic	USB CONNECTOR	N/A	51
USB 3	USB Data + (USBP)	Digital	3.0 V CMOS logic	USB CONNECTOR	N/A	49
USB 4	Ground			USB CONNECTOR	N/A	Ground Plane
RBF 1	Solar Safe N	Analog	N/A	3.5mm N.O. TS jack	N/A	40

*When external supply is connected to USB port

7.7 Battery PCB 2 System Bus Connections

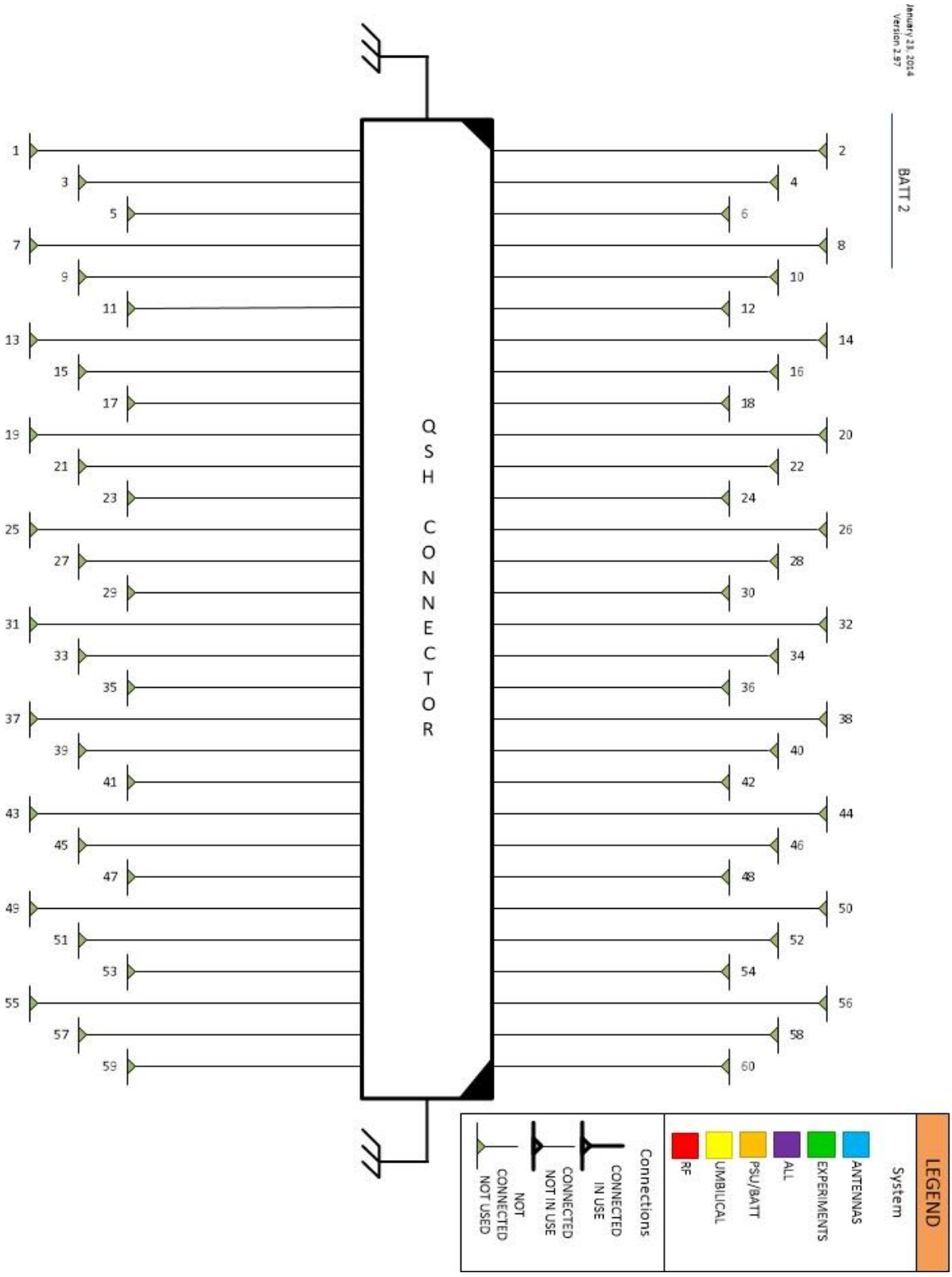


Figure 13: Battery 2 Bus Connection Pin Assignments

8 Experiment Payload Systems 1 through 4

8.1 System Requirements Applicable to Experiment Payload Systems 1-4

2.1.4	The satellite shall provide mass for an experiment payload up to 100 g.
2.1.5	The satellite shall provide volume for an experiment payload up to 95 x 95 x 15.7 mm.
2.2.1	The satellite avionics shall be designed for -40C to +70C operating temperature.
2.2.3	The satellite shall be designed to tolerate the radiation environment in orbit.
2.3.1	The satellite shall be designed for a minimum 5-year, on-orbit lifetime.
3.6.1	The satellite shall provide DC power for experiment payloads.
3.6.2	The satellite shall provide a means to activate and deactivate the experiment payloads.
3.6.3	The satellite shall provide a means to telemeter data from the experiment payloads.

8.2 Initial Surge Current Limits

8.2.1 All Experiment designs shall limit initial inrush current to 0.1 Amperes.

8.3 Volume Requirements Applicable to Experiment Payload System 1

8.3.1 No components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall protrude from the –Z surface of the PC board.

8.3.2 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 6.0 mm from the +Z surface of the PC board.

8.4 Interface Control Documents Applicable to Experiment 1 Payload System

AMSAT *Fox-1* IHU to Experiment 1 Interface Control Document

8.5 Volume Requirements Applicable to Experiment Payload Systems 2 and 3

8.5.1 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 1 mm from the –Z surface of the PC board.

8.5.2 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 6.0 mm from the +Z surface of the PC board.

8.6 Volume Requirements Applicable to Experiment System 4

8.6.1 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 1 mm from the –Z surface of the PC board.

8.6.2 Components, connections other than those connectors stipulated in section 10, and structures such as shielding or enclosures shall not protrude more than 5.0 mm from the +Z surface of the PC board.

8.7 Interface Control Documents Applicable to Experiment 4 Payload System

AMSAT *Fox-1* IHU to Experiment 4 Interface Control Document

8.8 PCB Plating Requirements Applicable to Experiment 1 Payload System

8.8.1 ENIG then selective flash gold four mounting pads. ENIG only will also be accepted if already fabricated.

8.9 PCB Plating Requirements Applicable to Experiment 2 Payload System

8.9.1 ENIG then selective flash gold four mounting pads. ENIG only will also be accepted if already fabricated.

8.10 PCB Plating Requirements Applicable to Experiment 3 Payload System

8.10.1 ENIG then selective flash gold four mounting pads. ENIG only will also be accepted if already fabricated.

8.11 PCB Plating Requirements Applicable to Experiment 4 Payload System

8.11.1 ENIG then selective flash gold four mounting pads..

8.12 Experiment Payload 1 Systems PCB Bus Connections

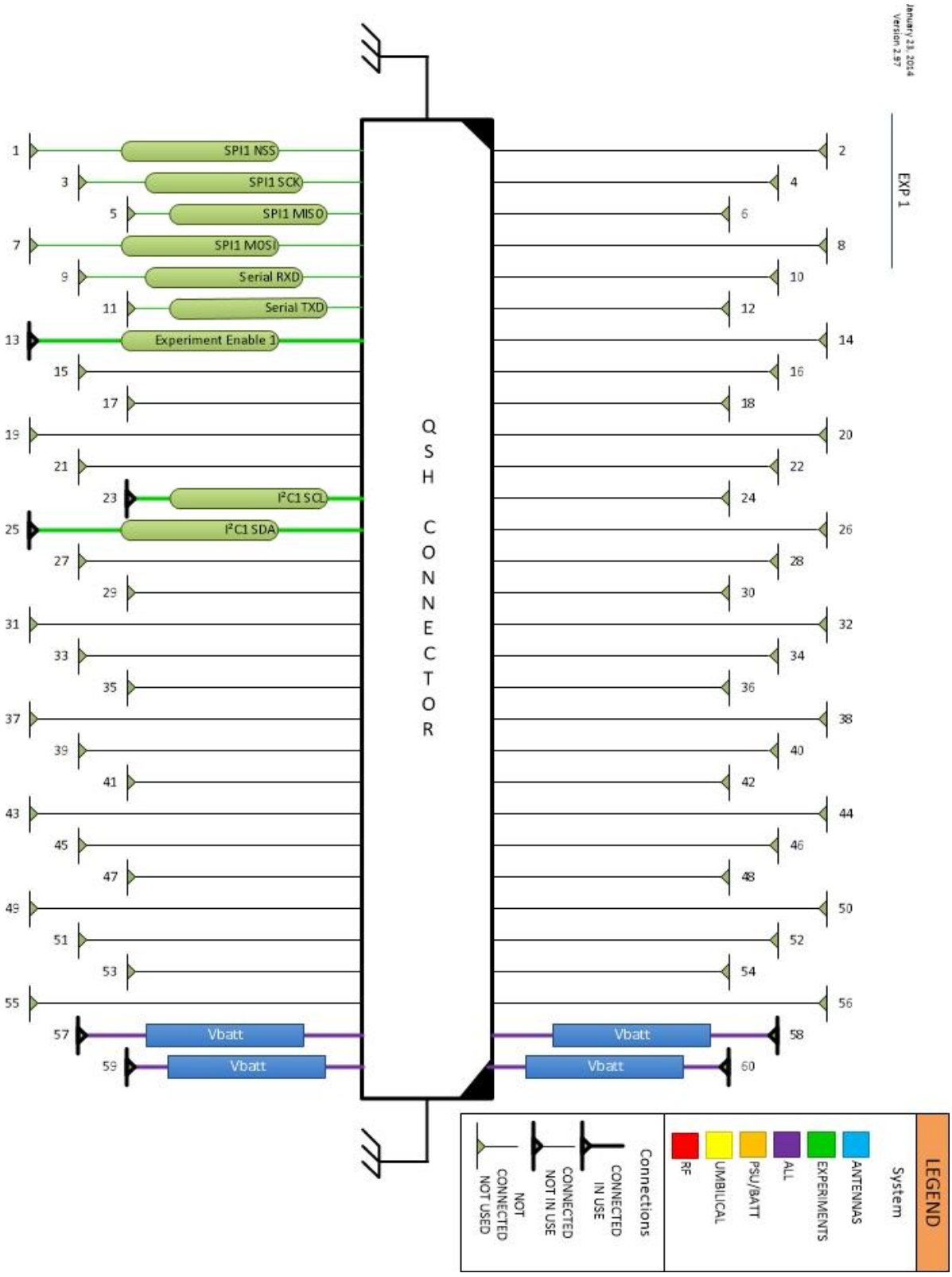


Figure 14: Experiment Payload 1-3 Systems Bus Connection Pin Assignments

8.13 Experiment Payload 4 System PCB Bus Connections

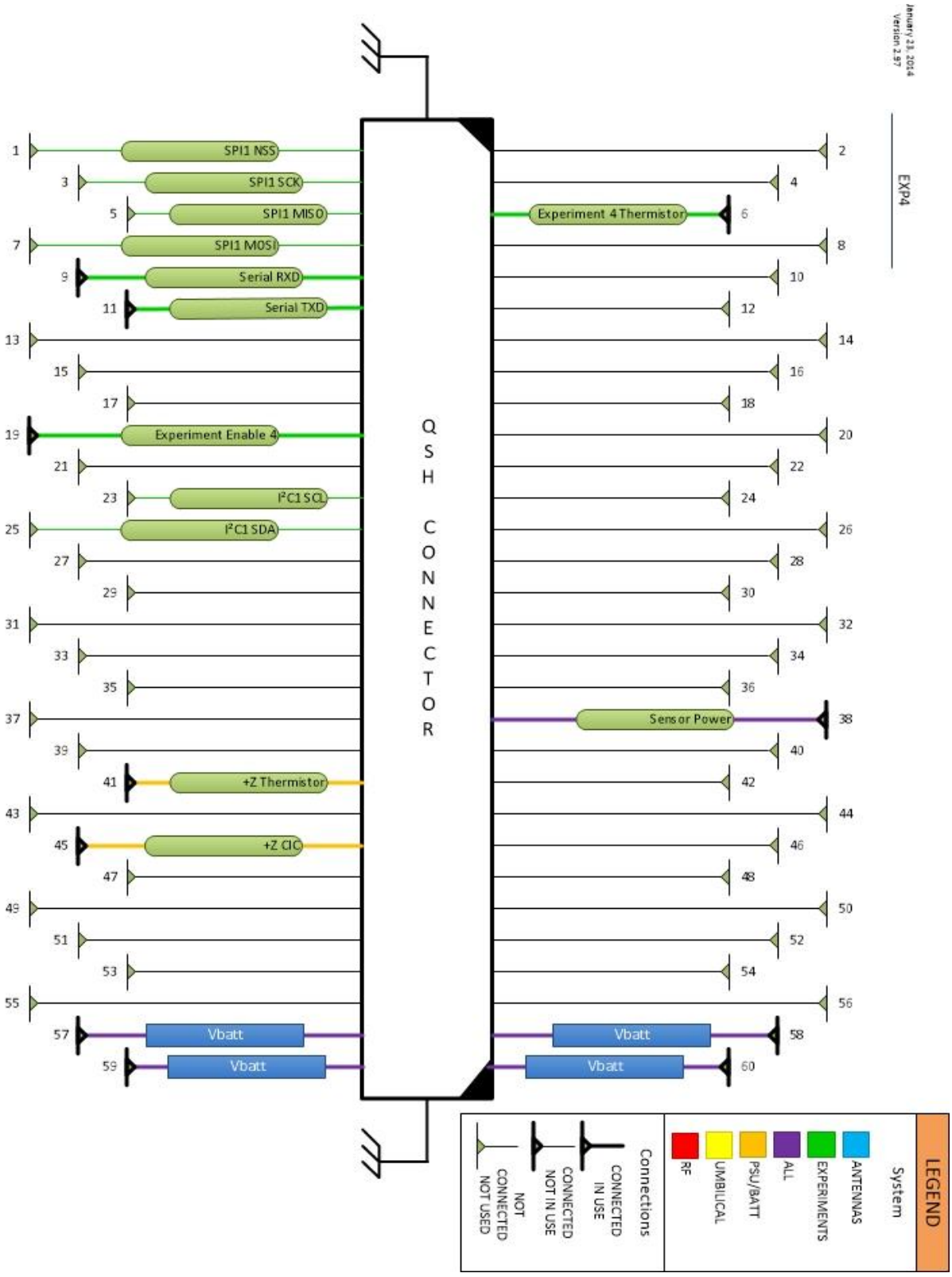


Figure 15: Experiment Payload 4 System Bus Connection Pin Assignments

8.14 Experiment Payload 4 System PCB External Connections

8.14.1 Three connections using Samtec FSI-105-06-L-S-AD connector
- **8.14.1.1** 1 contact +Z Solar Panel Thermistor
- **8.14.1.2** 1 contact +Z Solar Panel CIC +
- **8.14.1.3** 1 contact common or - for above two connections

Table 10: +Z PCB face FSI-105-06-L-S-AD connector mates to pads on +Z Solar Panel

Pin	Nomenclature	Type	Voltage	Source System	Load Z	Load System	Bus Pin
1	+Z Thermistor	Analog	N/A	N/A	N/A	PSU	41
2	N/C						
3	+Z Solar Panel Common						Ground Plane
4	N/C						
5	+Z CIC	Power	N/A	N/A	N/A	PSU	45

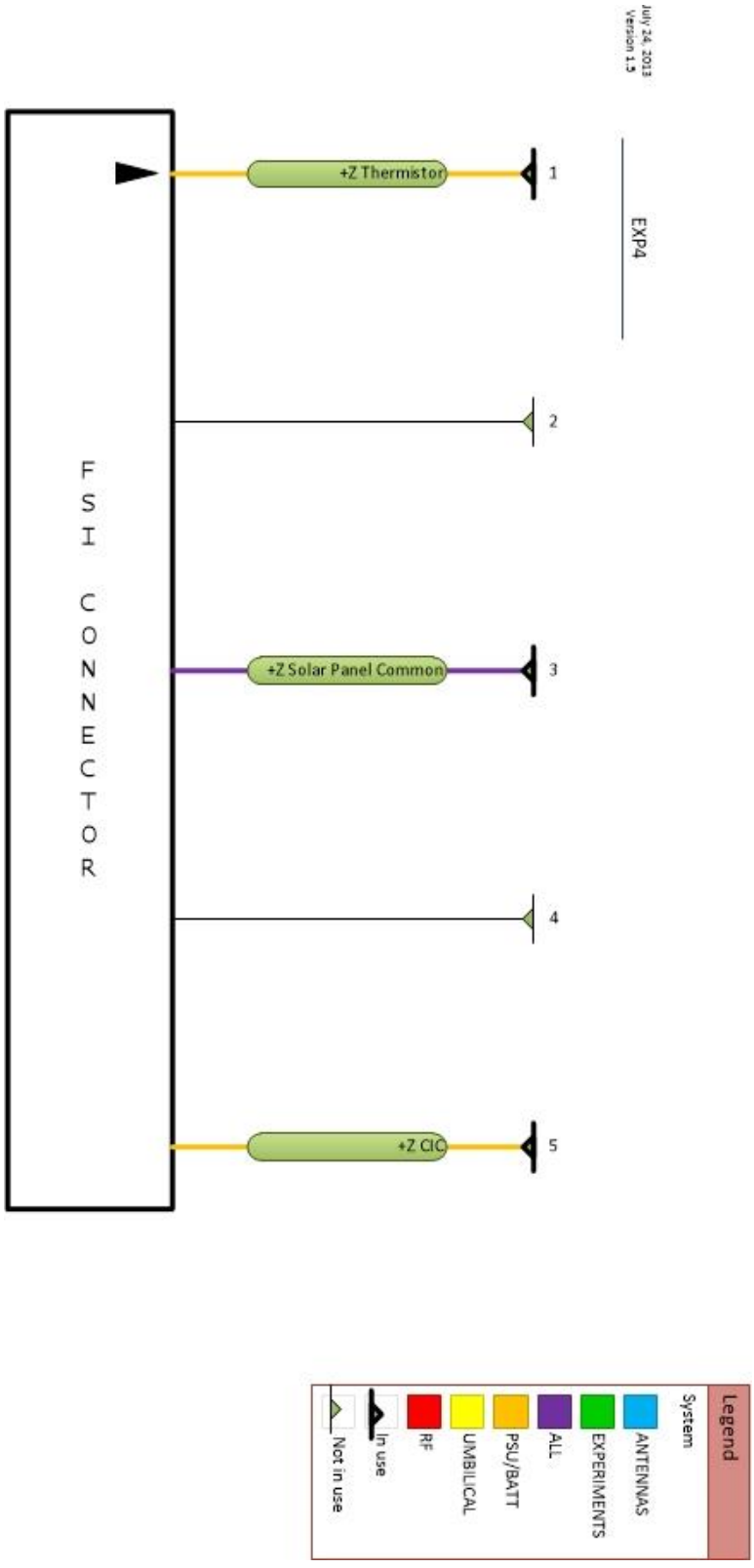
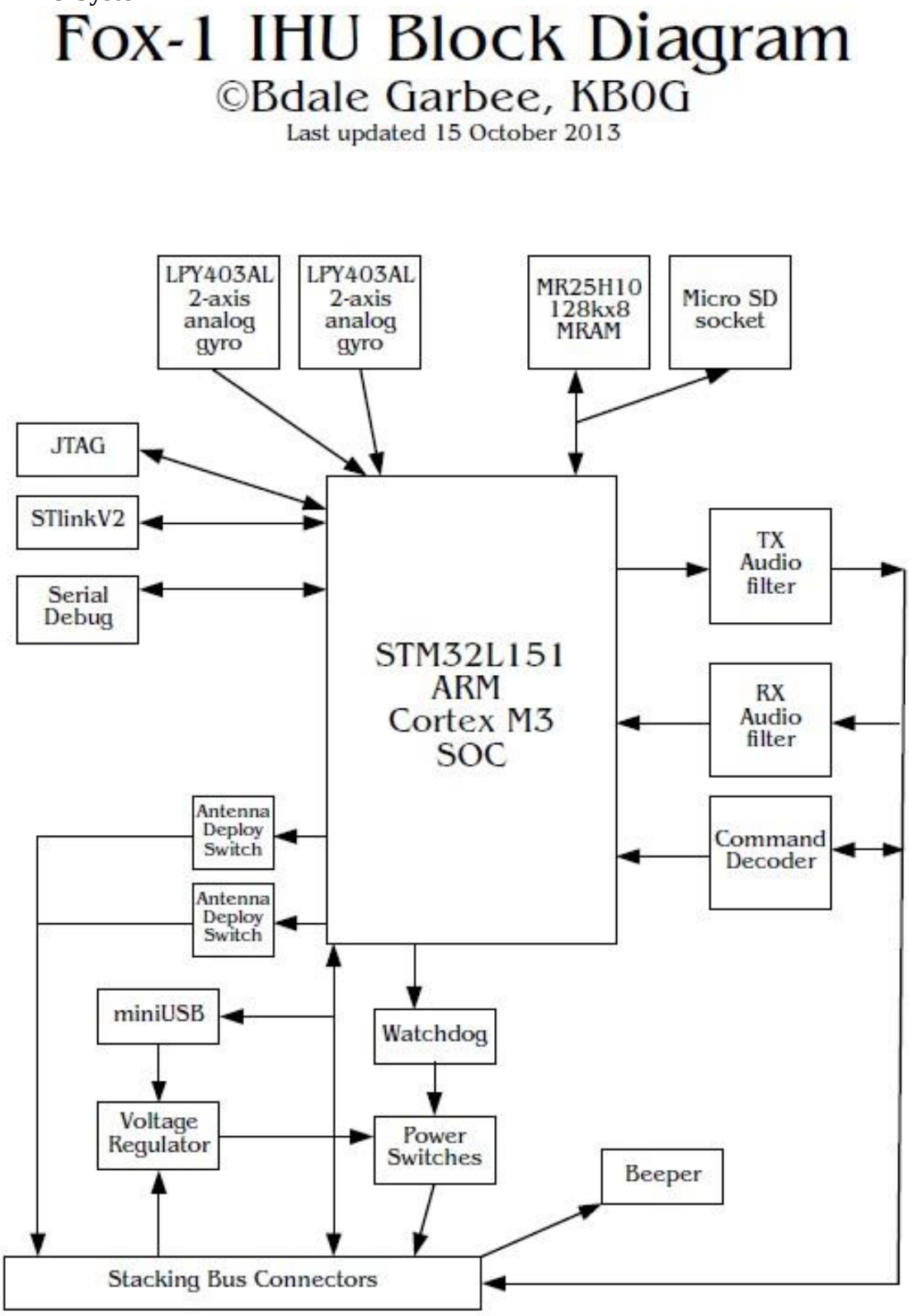


Figure 16: Experiment Payload 4 System FSI-105-06-L-S-AD Connection Pin Assignments

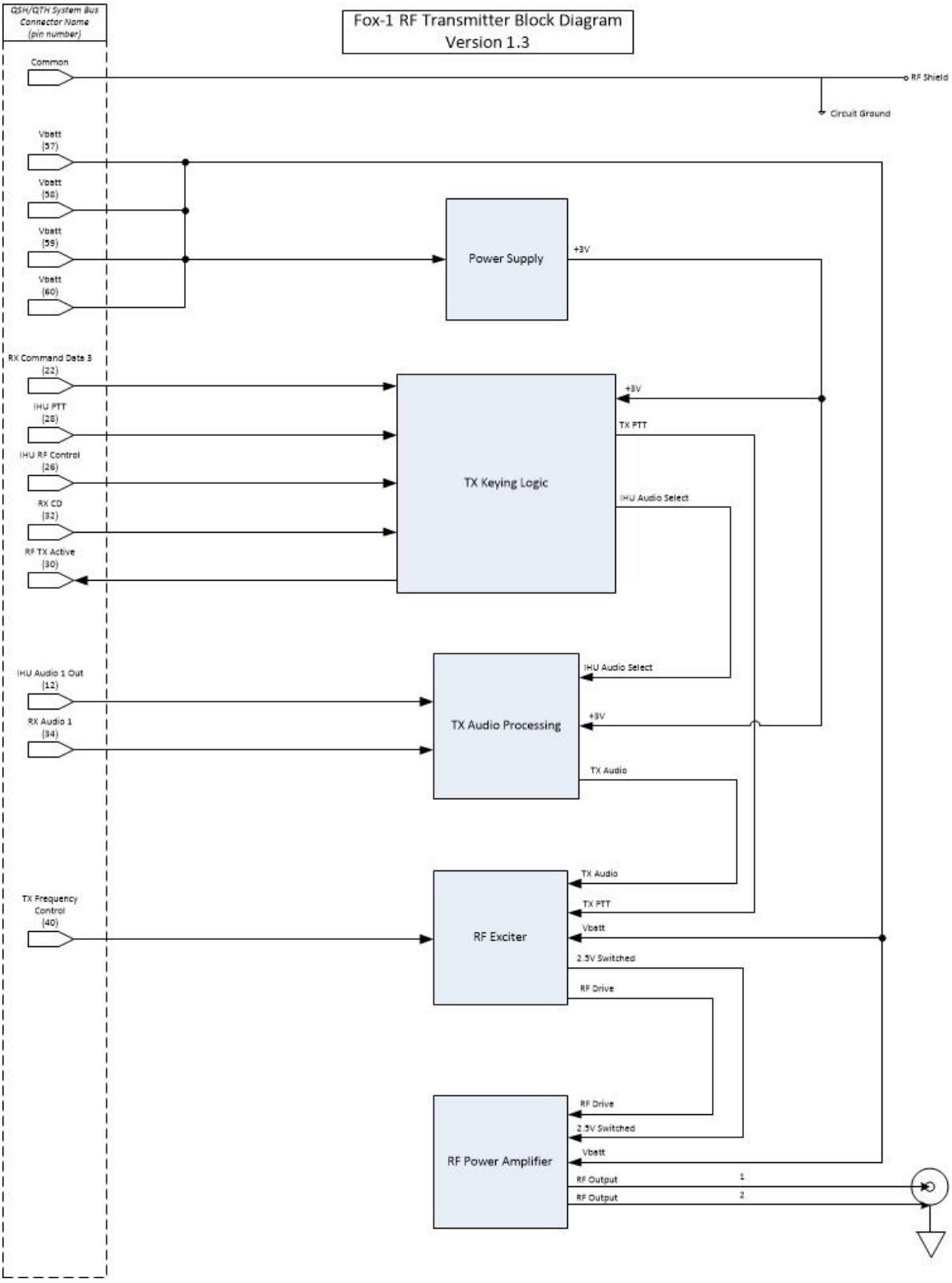
9 System Block Diagrams Reference

9.1 IHU System

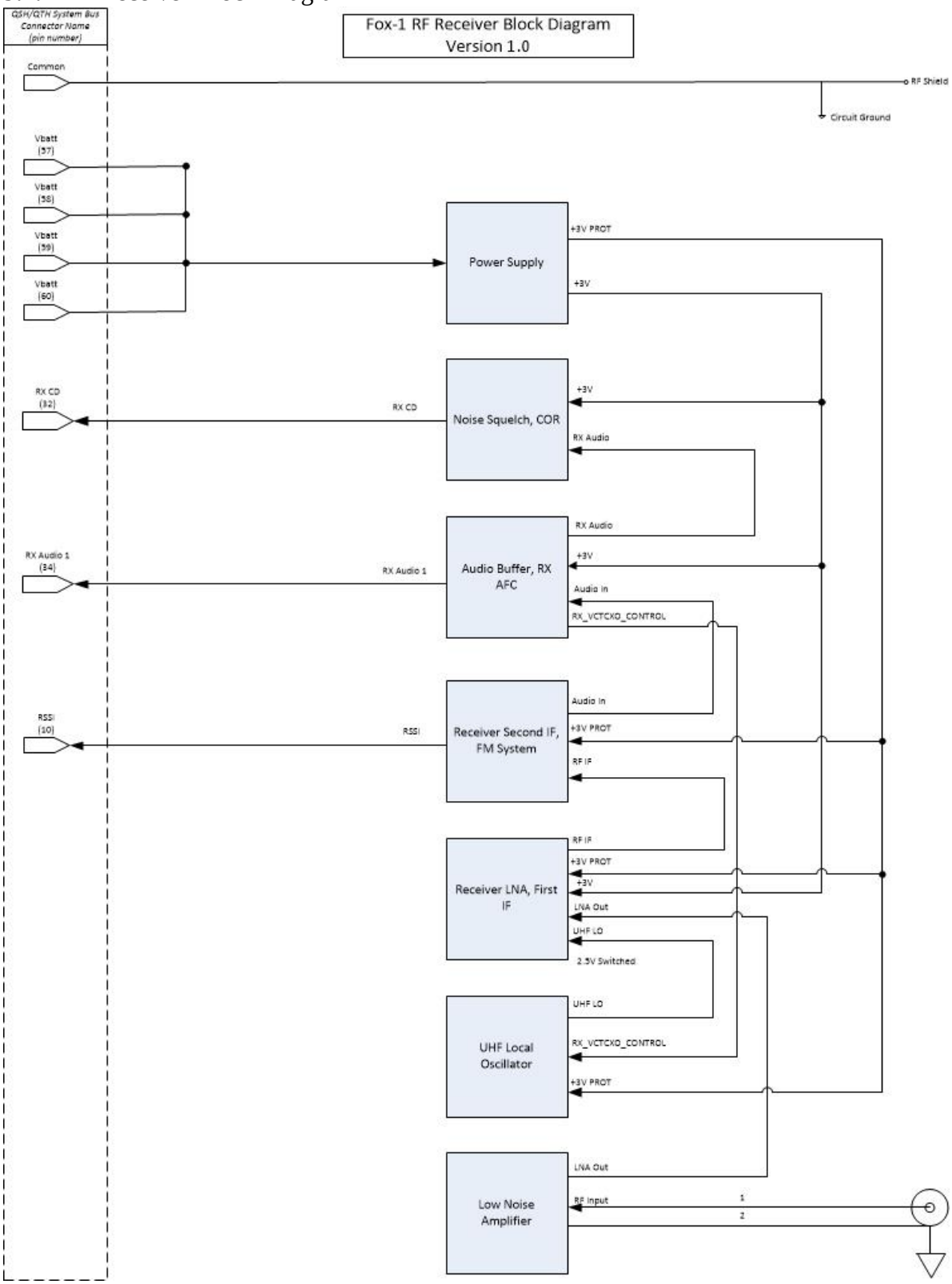


9.2 RF System

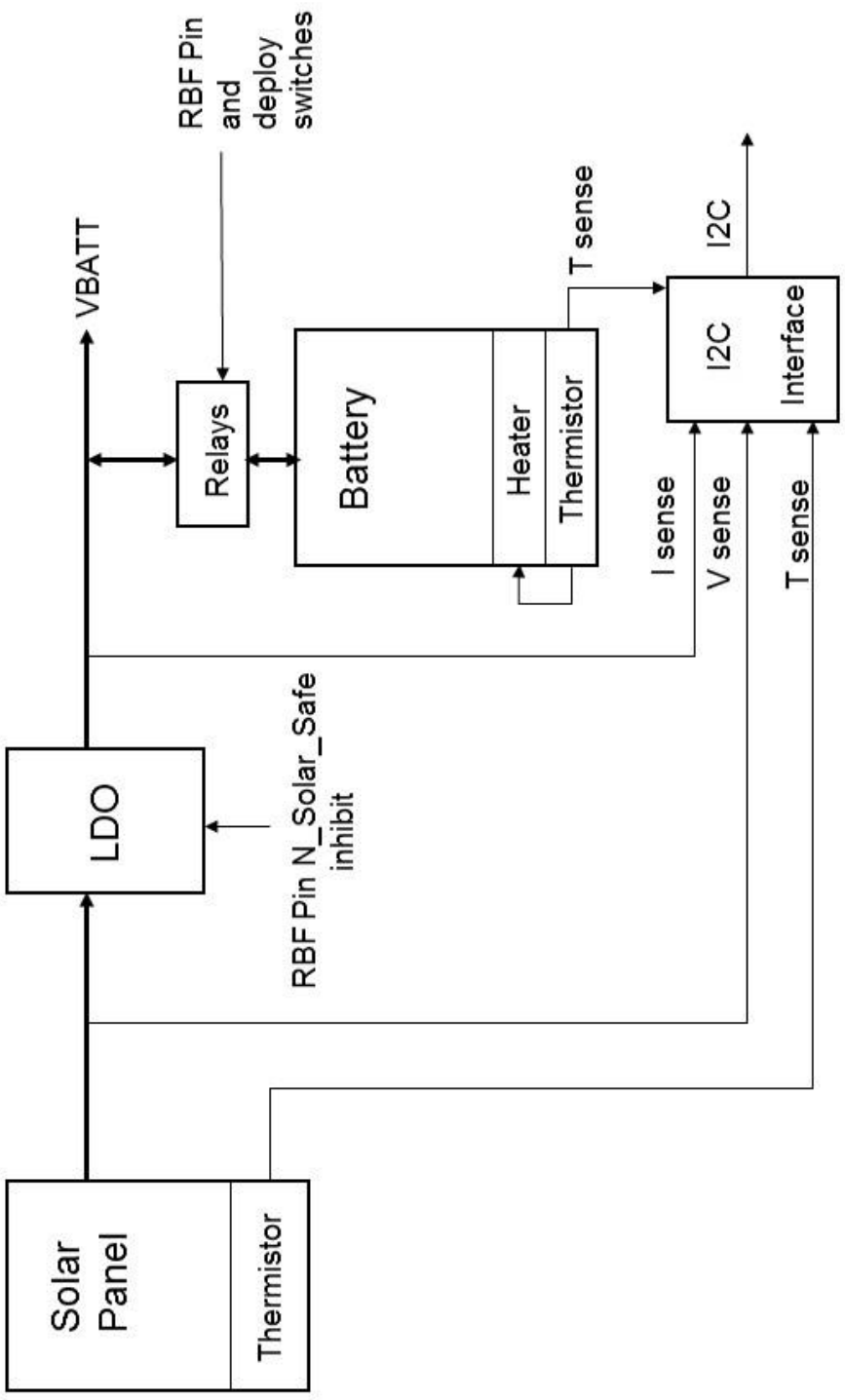
9.2.1 RF Transmitter Block Diagram



9.2.2 RF Receiver Block Diagram



9.3 PSU System



10 System Interconnection References

10.1 Bus Connectors

10.1.1 Samtec QTH-030-02-L-D-A and QSH-030-01-L-D-A connectors
10.1.2 QTH connector shall be mounted on the +Z surface of each circuit board except the Receive Antenna PCB / GPS Payload circuit board
10.1.3 QSH connector shall be mounted on the –Z surface of each circuit board

10.2 Bus Connector Documentation

10.2.1 Samtec QSH
10.2.2 Samtec QTH
10.2.3 Samtec QxH High Speed Characterization Report
10.2.4 Samtec QxH Single Ended Channel Properties

10.3 External Connectors

10.3.1 Samtec MEC1-105-02-L-D-NP-A connector mounted on +X, -X, +Y, -Y Solar Panels
10.3.2 Samtec FSI-105-06-L-S-AD connector mounted on -Z face of RF Transmitter System PCB and +Z face of Experiment Payload 4 System PCB

10.4 External Connector Documentation

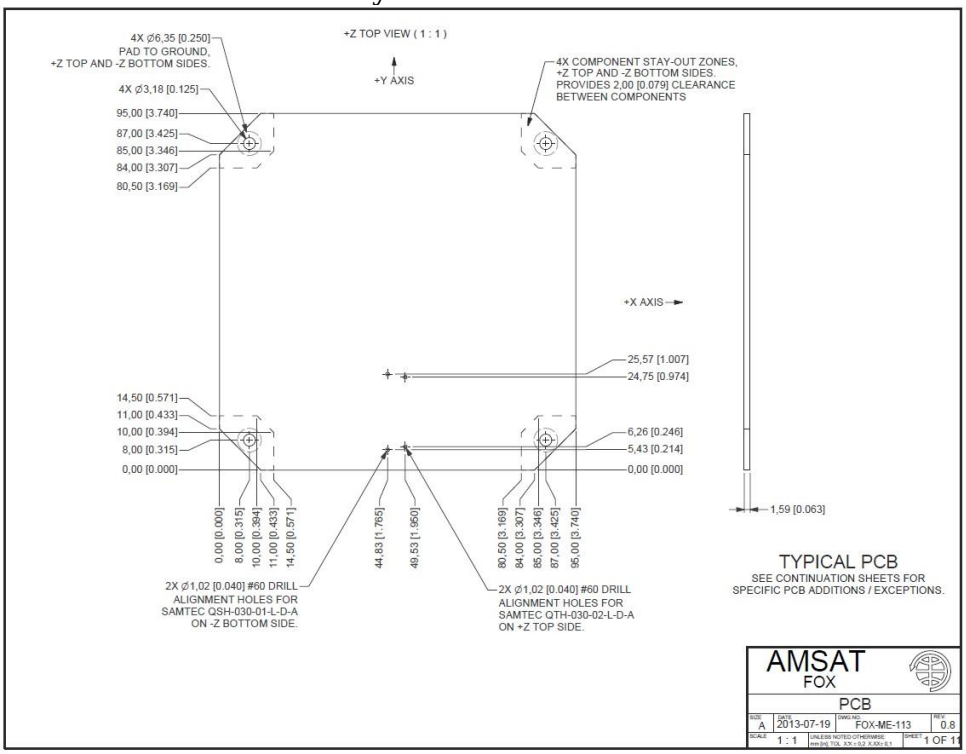
10.4.1 Samtec MEC1
10.4.2 Samtec MEC1 Qualification Testing
10.4.3 Samtec FSI

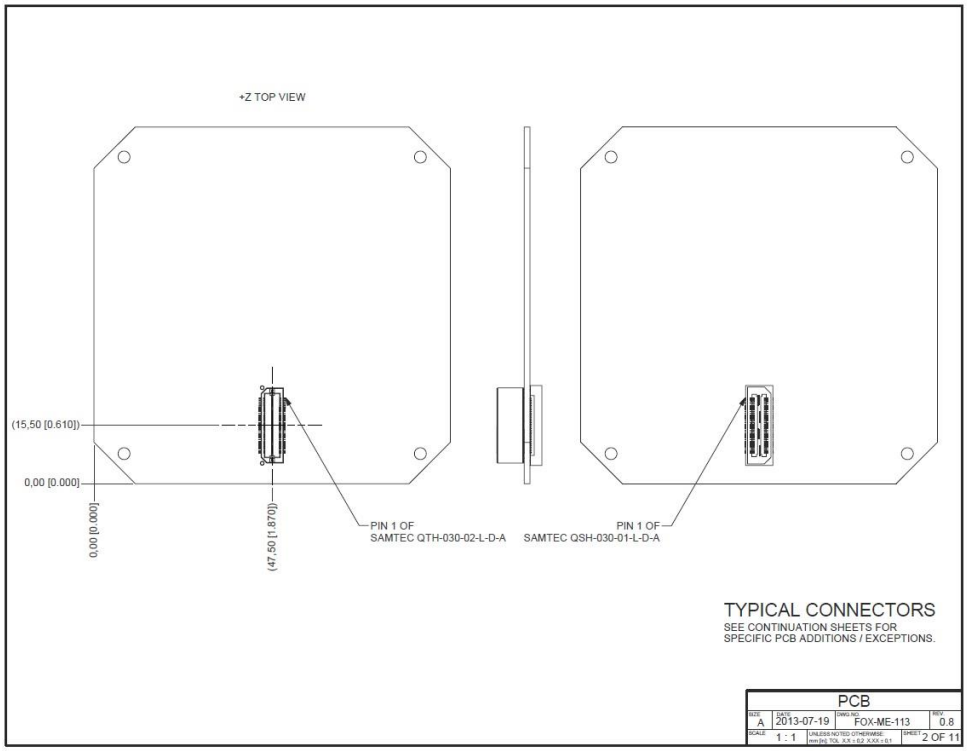
10.5 PCB Connector Layout Documentation

10.5.1 FOX-ME-113_PCB.pdf

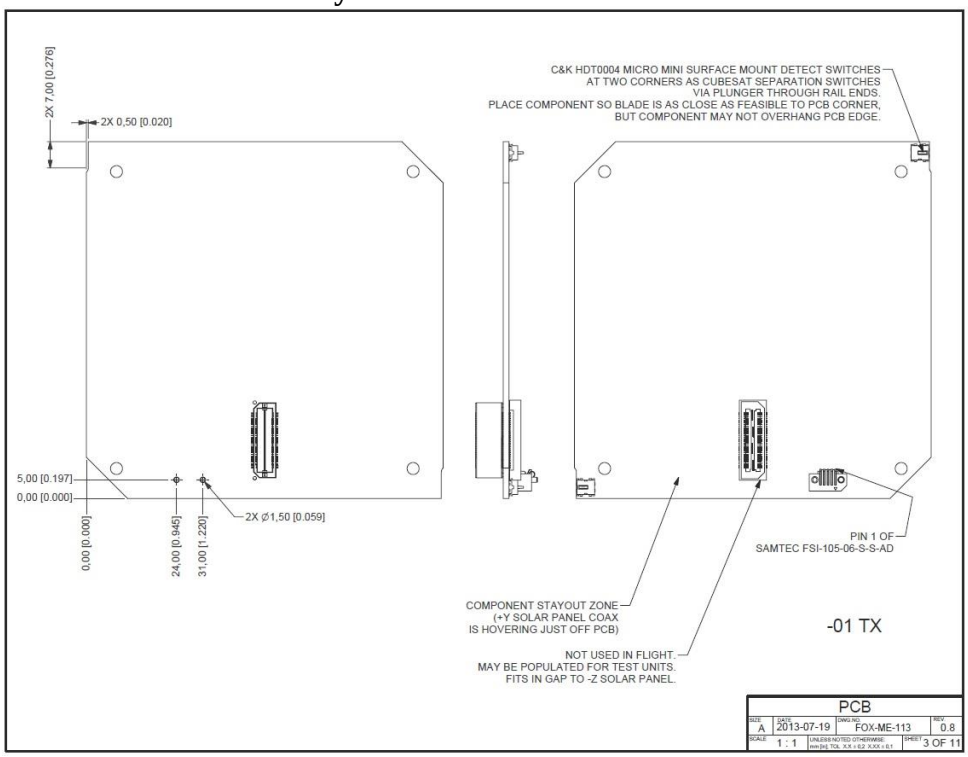
10.6 Systems PCB Connector Layout

10.6.1 Common to All Systems

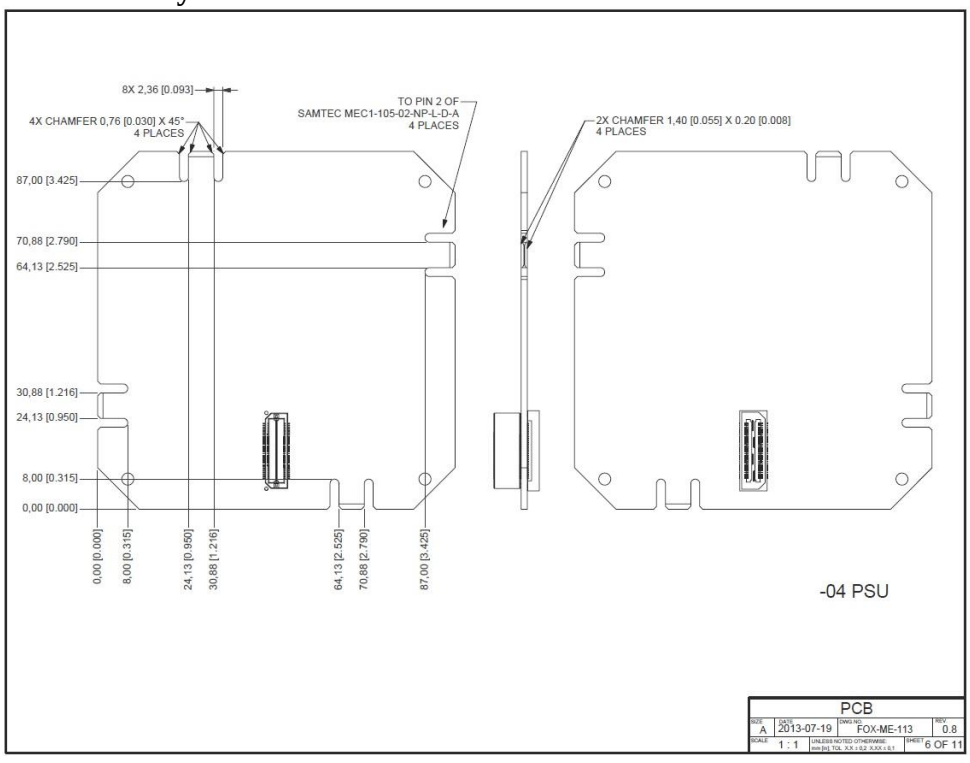




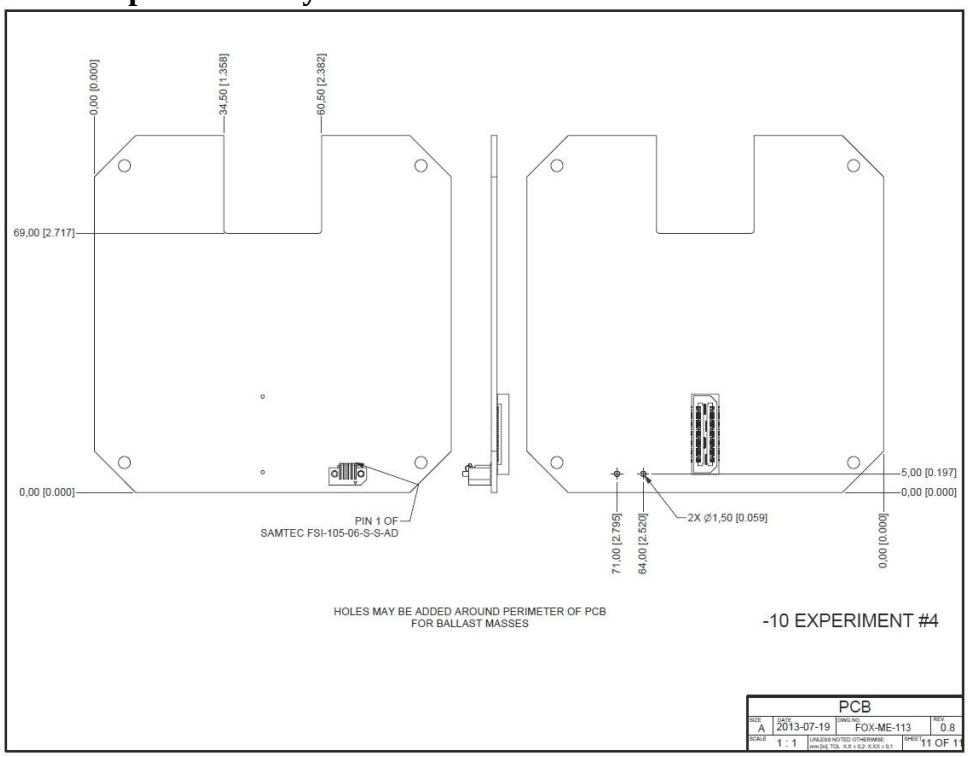
10.6.2 RF Transmitter System



10.6.3 PSU System



10.6.4 Experiment 4 System



Date: September 29, 2014
Version: Version 1.82

AMSAT *Fox-1*

System Requirements Specification

1 Introduction

This document specifies the system level technical requirements for the AMSAT *Fox-1* satellite project. This 1 Unit CubeSat is a part of the AMSAT Fox program and includes a subset of the technical capabilities envisioned for the overall program.

Fox-1 is specifically intended as a replacement for the failing AMSAT *Echo* (i.e. AO-51) satellite. *Echo* has been the most widely used amateur satellite due to its ability to provide basic radio communications with very simple ground station equipment. Its FM repeater provides very wide geographical coverage allowing amateur radio operators to communicate over substantial distances using just a handheld transceiver (i.e. a *walkie-talkie*) and a small handheld antenna. This so called "*EasySat*" mode is extremely valuable in providing an introduction to satellite communications and is often used for demonstrations given at schools, to scouting organizations and at amateur radio publicity events. *Fox-1* will not duplicate all of the features and modes of Echo but its primary mission is to provide an FM Transponder in order to allow continued access to this *EasySat* mode of communications.

In addition to its mission as a communications satellite, *Fox-1* will host an experiment payload. The satellite will reserve mass and volume for the experiment and will provide DC power and a communications facility. The experiment is expected to be provided by students at Penn State University – Erie through an AMSAT sponsored senior design project.

1.1 Document History

DATE	VERSION	SUMMARY
October 5, 2011	1.0	From Draft E
October 8, 2011	1.01	Fix typos in sections 1.2 and 3.5
October 9, 2011	1.02	Add Requirements Tracking
October 23, 2011	1.03	Additional Requirements Tracking
February 21, 2012	1.04	Update Section 3 and Formatting changes
April 18, 2012	1.05	Correction in Section 4
April 22, 2012	1.06	Correct link in Section 1.4 item 2
April 29, 2012	1.1	Revised 3.12.3, 3.12.7, 3.12.8, 3.13.3, 3.13.4, figure 1 to remove RESET and add IHU OFF and IHU ON commands
August 2, 2012	1.11	Added hidden text for requirements tracking to be shown in System Design Specification
September 4, 2012	1.12	Added the previously missing “Table 6” label
October 17, 2012	1.2	Changed mode descriptions in 3.13.1 Table 6; changed 3.9.2, 3.9.3, 3.9.4, 3.9.5, 3.9.6, 3.9.7 to reflect IHU involvement; changed COMMAND MODE to DATA MODE
April 25, 2013	1.3	3.10.2 Remove PA Temperature, add TX T as RF Transmitter Temperature, OSC T as referring to TX oscillator no longer measured changed to read RX oscillator only
August 20, 2013	1.4	Requirements 3.5.5, 3.6.1, 3.9.6, 3.10.2, 3.11.1, 3.12.4, 3.12.6, 3.13.7.1, 3.13.7.2, 3.13.8, 3.13.9 modified, removed or added to reflect the evolving satellite design
January 10, 2014	1.5	Changes to 3.12.3, 3.12.4, 3.13.2, 3.13.5, 3.13.5.1, 3.13.5.2, 3.13.7, 3.13.7.3, 3.13.7.3.1, 3.13.7.3.2, 3.13.11, 3.13.12 to add Safe Mode
January 20, 2014	1.6	Change 3.13.7.3 to go directly to Safe Mode, remove 3.13.7.3.1 and 3.13.7.3.2
January 23, 2014	1.7	Modified 3.13.2 (figure 1), 3.13.11, added 3.13.11.1
February 10, 2014	1.71	Added “Experiments are powered off” to Table 6 under Safe Mode

DATE	VERSION	SUMMARY
April 17, 2014	1.72	Bring Table 5 commands in line with Command and Control Document, remove PSU reference from 3.12.8 and 3.12.9
August 16, 2014	1.8	Update to actual operating values 3.13.11, 3.13.11.1, 3.12.3, 3.13.1, 3.13.7, 3.13.7.1, 3.13.7.2
September 8, 2014	1.81	Update to actual operating values 3.9.3, 3,9,6, update Table 5, add 3.12.12 and 3.12.13
September 29, 2014	1.82	Update 3.9.3, 3.9.4 to allow for variable hang timer

1.2 Document Scope

The purpose of this document is to specify the technical requirements of the satellite at the system (i.e. "black box") level. It is intended to be used by the hardware, software and mechanical designers to develop the architecture/high-level design specifications. It is also intended to be used for test planning and development.

1.3 Document Format

This document provides the requirements in numbered format. Each requirement is assigned a unique number. Additional information such as comments or examples that are provided for guidance or clarity is *italicized* to distinguish them from requirements.

1.4 References

1. AMSAT *Fox-1,* Concept of Operations, Version 1.0, September 19, 2011
2. CubeSat Design Specification Rev. 12. by The CubeSat Program Cal Poly SLO available from: http://www.cubesat.org/images/developers/cds_rev12.pdf
3. Launch Services Program, Program Level Poly Picosatellite Orbital Deployer (PPOD) and CubeSat Requirements Document LSP-REQ-317.01 Revision Basic (from NASA)
4. ITU Radio Regulations, Edition of 2008. available from http://www.itu.int/publ/R-REG-RR-2008/en

2 General Requirements

2.1 CubeSat Requirements

2.1.1 The satellite shall meet the requirements specified in the CubeSat Design Specification Rev. 12.

2.1.2 The satellite shall meet the requirements specified in the NASA LSP-REQ-317.01 Revision Basic.

2.1.3 The satellite shall meet the requirements for a 1 unit (single) CubeSat.

2.1.4 The satellite shall provide mass for an experiment payload up to 100 g.

2.1.5 The satellite shall provide volume for an experiment payload up to 95 x 95 x 15.7 mm.

2.2 Environmental Requirements

2.2.1 The satellite avionics shall be designed for -40C to +70C operating temperature.

2.2.2 The satellite shall be designed to operate in a 650 km, sun-synchronous, circular orbit.

2.2.3 The satellite shall be designed to tolerate the radiation environment in orbit.

2.3 Reliability Requirements

2.3.1 The satellite shall be designed for a minimum 5-year, on-orbit lifetime.

2.4 RF Frequency Requirements

2.4.1 All RF transmitters shall meet or exceed the requirements specified in the ITU Radio Regulations, Technical Characteristics, Volume 3, article 3.

2.4.2 All satellite uplinks shall be in the 70 cm band of the amateur satellite service.

2.4.3 All satellite downlinks shall be in the 2 meter band within the amateur satellite service.

2.4.4 All satellite transmitter and receiver frequencies shall deviate by no more than 5 parts-per-million from the specified values including initial accuracy and temperature variation.

2.4.5 All satellite frequencies shall be coordinated with the IARU.

Note that the band plan with the actual coordinated frequencies will be specified in a separate document.

3 Functional Requirements

3.1 Antenna System

3.1.1 The satellite shall include a deployable antenna system.

3.2 Attitude Control

3.2.1 The satellite shall incorporate passive magnetic stabilization to align the deployed antennas with the magnetic field of the earth.

3.3 Access Ports

3.3.1 The satellite shall include a "Remove Before Flight" pin as per the CubeSat Design Specification.

3.3.2 The satellite shall include an umbilical port as per the CubeSat Design Specification.

3.4 Pre-launch Features

3.4.1 The satellite battery and photovoltaic panels shall be electronically disconnected from the avionics when the "Remove Before Flight" pin is inserted, regardless of the state of the deployment switch(es).

3.4.2 The satellite shall provide the means to charge the battery via the umbilical port while integrated with the P-POD.

3.4.3 The satellite shall provide the means to run diagnostic tests via the umbilical port while integrated with the P-POD.

3.5 Power

3.5.1 The satellite shall produce electrical power from sunlight.

3.5.2 The satellite shall produce electrical power while in sunlight regardless of orientation and while tumbling or spinning.

3.5.3 The satellite shall produce sufficient average electrical power to operate continuously in the orbit of maximum eclipse.

3.5.4 The satellite shall provide sufficient battery capacity to operate continuously in the orbit of maximum eclipse.

3.6 Experiment

3.6.1 The satellite shall provide DC power for experiment payloads.

3.6.2 The satellite shall provide a means to activate and deactivate the experiment payloads.

3.6.3 The satellite shall provide a means to telemeter data from the experiment payloads.

Note that the experiment payloads will be specified in a separate documents.

3.7 RF Uplink

3.7.1 The satellite shall include an FM uplink receiver.

3.7.2 The receiver shall have specifications as shown in Table 1.

Table 1

Sensitivity	-120 dBm for 12 dB SINAD (min.)
FM Deviation	5 kHz
Audio Bandwidth	3 kHz
Input Frequency Acceptance	Receiver shall accept signals that are off frequency by ±2.5 kHz (min.)

3.8 RF Downlink

3.8.1 The satellite shall include an FM downlink transmitter.

3.8.2 The transmitter shall have specifications as shown in Table 2.

Table 2

Power Output	400 mW (min.)
FM Deviation	5 kHz
Audio Bandwidth	3 kHz

3.8.3 The transmitter shall provide a means to prevent over modulation.

3.9 FM Transponder

3.9.1 The satellite shall provide an FM transponder via the RF uplink and RF downlink.

3.9.2 In Transponder Mode, the IHU shall detect the presence of a 67 Hz CTCSS tone on the uplink.

3.9.3 In Transponder Mode, the downlink transmitter shall be keyed (*i.e. PTT-on*) by the IHU for a minimum of 30 seconds following detection of the 67 Hz CTCSS tone.

3.9.4 In Transponder Mode, the downlink transmitter shall stay on continuously as long as the 67 Hz CTCSS tone is detected at least once during the period the transmitter is being keyed (*i.e. PTT-on*).

3.9.5 In Transponder Mode, the 67 Hz CTCSS tone is not required for a received signal to be repeated on the downlink, once the transmitter has been keyed.

3.9.6 In Transponder Mode, if the downlink transmitter has been un-keyed for a period of 2 minutes, the satellite shall send "HI THIS IS AMATEUR RADIO SATELLITE FOX 1" as a voice announcement on the downlink transmitter.

3.9.7 In the event of shutdown or failure of the IHU, the satellite shall default to simple carrier operated repeater operation.

3.10 Telemetry Data

3.10.1 The satellite shall collect telemetry data.

3.10.2 The telemetry data shall include at a minimum, measured parameters as shown in Table 3.

Table 3

Parameter Name	Description
CELL V	Voltages of battery cells
PANEL V	Voltages of solar panels
TOTAL I	Total DC current out of power system
PA I	DC current into RF power amp
BATTERY T	Temperature of battery
PANEL T	Temperatures of solar panels
TX T	Temperature of RF transmitter card
RX T	Temperature of RF receiver card

3.10.3 The measured parameters shall be sampled at least every 15 seconds.

3.10.4 The minimum and maximum values of each of the measured parameters shall be saved in non-volatile memory.

3.10.5 The telemetry data shall also include at a minimum, calculated parameters as shown in Table 4.

Table 4

Parameter Name	Description
UP TIME	Total seconds since avionics power-up or reset
SPIN	Satellite spin rate and direction

3.10.6 A telemetry frame shall include the current measured values, the saved minimum and maximum values, and the current calculated values.

Note that the telemetry interface will be specified in a separate document.

3.11 Telemetry Transmission

3.11.1 The satellite shall send slow speed telemetry using FSK on the RF downlink.

3.11.2 The FSK shall use the frequency spectrum below the audible range.

3.11.3 The telemetry shall be transmitted simultaneously with any transponder communications.

3.11.4 The telemetry transmission shall include telemetry frames.

3.11.5 The telemetry transmission shall include experiment data.

3.12 Command Capability

3.12.1 The satellite shall provide the means to process commands sent via the RF uplink from a ground control station.

3.12.2 The commands received via the RF uplink shall not be repeated on the RF downlink.

3.12.3 The following commands shall be provided, as shown in Table 5.

Table 5

Command	Operation
SAFE MODE	Enter Safe Mode
INHIBIT TX	Inhibit RF transmission
ENABLE TX	Enable RF transmission
IHU OFF	Power off IHU
IHU ON	Power on IHU
CLEAR	Clear stored telemetry
TRANSPONDER MODE	Enter Transponder Mode
DATA MODE	Enter Data Mode
ENABLE AUTO-SAFE	Enable Auto-Safe Mode
DISABLE AUTO-SAFE	Disable Auto-Safe Mode

3.12.4 A SAFE MODE command shall cause the satellite to enter the Safe Mode.

3.12.5 An INHIBIT TX command shall disable the RF transmitter.

3.12.6 An ENABLE TX command shall enable the RF transmitter.

3.12.7 An IHU OFF command shall cause the IHU System to power off.

3.12.8 An IHU ON command shall cause the IHU System to power on.

3.12.9 A CLEAR command shall cause the satellite to clear the saved minimum and maximum telemetry parameter values.

3.12.10 A TRANSPONDER MODE command shall cause the satellite to enter the Transponder Mode.

3.12.11 A DATA MODE command shall cause the satellite to enter the Data Mode.

3.12.12 An ENABLE AUTO-SAFE command shall enable the auto-safe mode state.

3.12.13 A DISABLE AUTO-SAFE command shall disable the auto-safe mode state.

Note that the control interface will be specified in a separate document.

3.13 On-Orbit Operating Modes

3.13.1 The satellite shall provide on-orbit operating modes as shown in Table 6.

Table 6

Name	Description
Startup Mode	Wait 50 minutes and deploy antennas
Safe Mode	Wait 120 seconds then begin 10 second beacon sequence Experiments are powered off

Transponder Mode	FM transponder; PTT and low speed telemetry via IHU
Data Mode	FM transmitter; PTT and high speed telemetry via IHU

3.13.2 The satellite shall transition between modes as shown in Figure 1.

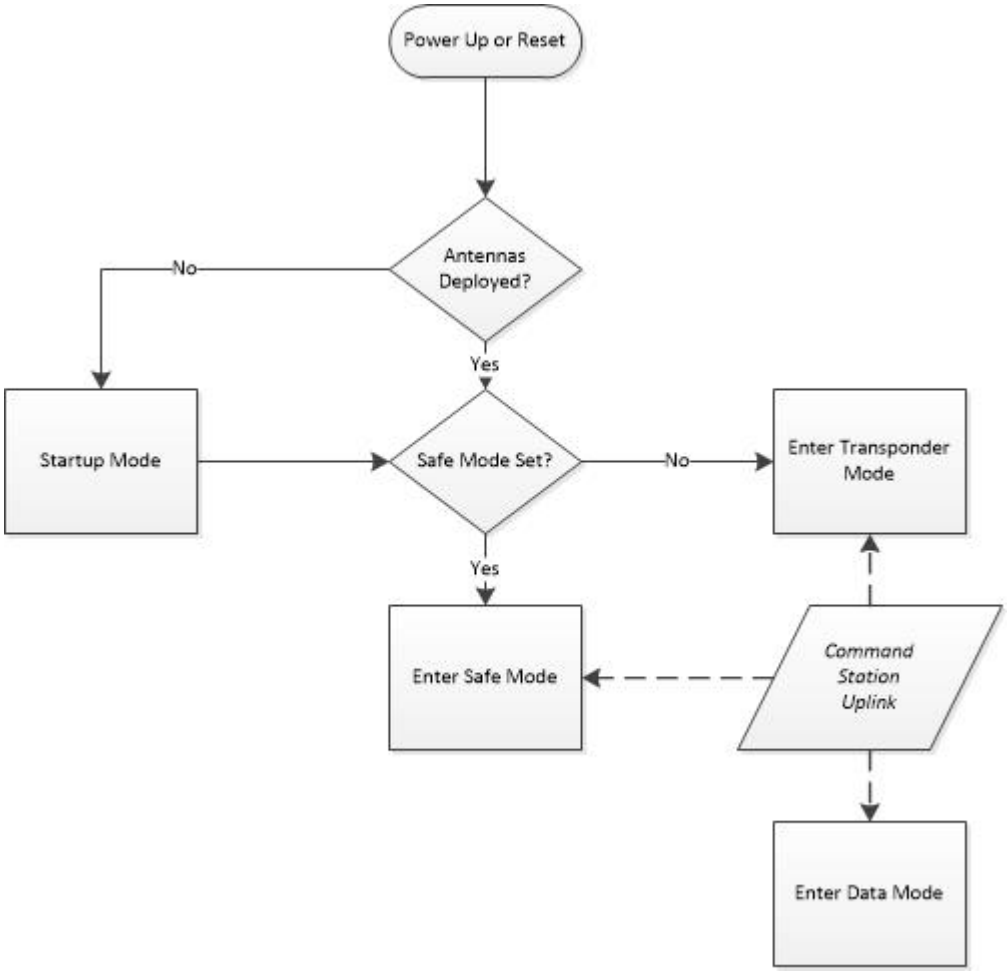


Figure 1. On-Orbit Operating Modes

3.13.3 Upon power-up of the avionics, the satellite shall begin operation from the "Power-up" state as shown in Figure 1.

3.13.4 An IHU ON Command shall cause the satellite to begin operation from the "Power-up" state as shown in Figure 1.

3.13.5 If the antennas have been deployed, the satellite shall determine whether the last state was Safe Mode.

3.13.5.1 If the last state was Safe Mode the satellite shall enter Safe Mode.

3.13.5.2 If the last state was not Safe Mode the satellite shall enter Transponder Mode.

3.13.6 If the antennas have not been deployed, the satellite shall enter the Startup Mode.

3.13.7 In Startup Mode, the satellite shall wait 50 minutes, then deploy the antennas.

3.13.7.1 During the 50 minute wait the IHU shall flash a red LED.

3.13.7.2 During the 50 minute wait the IHU shall sound a 1 kHz beeping tone.

3.13.7.3 After the antennas have been deployed the satellite shall enter Safe Mode.

3.13.8 In Transponder Mode, the transponder and the slow speed telemetry shall be active.

3.13.9 In Data Mode, the high speed telemetry shall be active and the transponder shall not be active. *(i.e. signals that appear on the uplink shall not be repeated on the downlink.)*

3.13.10 If another Data Mode command is not received, the satellite shall automatically enter Transponder Mode 24 hours after having entered Data Mode.

3.13.11 In Safe Mode the satellite shall wait 120 seconds then transmit a 10 second beacon.

3.13.11.1 The 120 second wait and 10 second beacon cycle will be repeated as long as the satellite is in Safe Mode.

3.13.12 The RF uplink shall be monitored for commands in all modes.

4 External Interface Documents

To fully specify the satellite technical requirements, the following documents must also be provided;

1. IARU Coordinated Frequency Plan
2. Downlink Specification
3. Control Interface Specification
4. Experiment Payload Specifications

5 Summary

The *Fox-1* satellite will be AMSAT's first CubeSat. Its primary mission is to provide an FM Transponder communications capability. The secondary mission is to host a university-provided experiment payload.

Date: November 7, 2014
Version: Version 1.10

AMSAT *Fox-1A*

IHU to Experiment 1 Interface Control Document

1 Introduction

This document specifies the message interface between the Internal Housekeeping Unit (IHU) and the Experiment System in Position 1 of the satellite, known as the Vanderbilt University Vulcan Payload and abbreviated herein as EXP1.

1.1 Document History

DATE	VERSION	SUMMARY
March 3, 2013	1.00	Initial version
March 7, 2013	1.01	Correct use of I²C (1.2) and EXP1 (2.3.3)
March 31, 2013	1.02	Command Message CRC8 to include address byte, change to commands, modified figure 3, deleted figure 4
March 31, 2013	1.03	Delete TYPE from message tables, add SET TIME response return values
March 31, 2013	1.04	Add CMD_VERSION_ERR to Error Code table
April 2, 2013	1.05	Correct 6.5 Figure 3, remove 0x0005, 0x0201, 0x0210, 0x0281, 0x0300, and 0x0301 commands
September 17, 2013	1.06	Change type format to exclude code type, add Min/Max Values
October 7, 2013	1.07	Revised Table 1 and 3.2.1 added 3.5.1.1 for clarification on Experiment Enable 1 states
November 7, 2013	1.08	Added 3.1.2 and 3.1.3 regarding minimum power levels for experiment operation
May 21, 2014	1.09	Revised 3.1.2 and 3.1.3 to read <= 3.3V
November 7, 2014	1.10	Update HALT value to 0x05 in Table 6

1.2 Document Scope

This document will specify the control of EXP1, the messaging format, and the I²C bus hardware operation for the communications between the IHU and the EXP1.

1.3 References

1. AMSAT *Fox-1*, System Requirements Specification
2. AMSAT *Fox-1*, System Design Specification
3. AMSAT *Fox-1*, IHU Software Architecture Specification
4. Vanderbilt University Vulcan Payload Interface Control Document

2 General Messaging Requirements

2.1 Link Protocol Requirements

2.1.1 The IHU shall initiate a command to the EXP1.

2.1.2 The EXP1 shall send a reply to each IHU request.

2.1.3 Message bit order shall be Big Endian.

2.1.4 The IHU shall determine the action to be taken in the event of an invalid, improper, or missing message from the EXP1.

2.1.5 The EXP1 shall take no action in the event of an invalid or improper message from the IHU.

2.1.6 Message byte order shall be Big Endian.

2.2 General Message Requirements

2.2.1 Each message shall contain a header block.

2.2.2 Each message shall contain a packet error check (PEC) in the form of CRC8.

2.2.2.1 The message address byte shall be included when calculating the CRC8.

2.3 I²C 1 Bus Hardware Interface Requirements

2.3.1 The I²C Vdd shall be 3.0V.

2.3.2 The bus speed shall be Fast (400kbit/s).

2.3.3 The EXP1 I²C 7 bit address shall be 0x2A.

3 Experiment Operation

3.1 Experiment Power Control

3.1.1 The IHU shall exert control over the power state of the EXP1 by the Experiment Enable 1 pin on the satellite bus as shown in Table 1.

Table 1

Pin State	Description
High	Power On Experiment
Low or high-impedance	Power Off Experiment

3.1.2 The IHU shall not power on the experiment if the power bus voltage (VBATT) is less than or equal to 3.3 Volts.

3.1.3 The IHU shall perform the Experiment Cease Operation Sequence and the Experiment Power Off Sequence if the power bus voltage (VBATT) falls to less than or equal to 3.3 Volts while the experiment is powered on.

3.2 Experiment Power On Sequence

3.2.1 The IHU shall set and hold the Experiment Enable 1 pin HIGH.

3.2.2 The IHU shall not send any message to the EXP1 for a minimum of 100 milliseconds.

3.2.3 The IHU shall send a Set Time command to the EXP1.

3.3 Experiment Begin Operation Sequence

3.3.1 Upon completion of the Power On sequence the IHU shall send a Set Run State Active command message to the EXP1.

3.4 Experiment Cease Operation Sequence

3.4.1 The IHU shall send a Set Run State Halt command message to the EXP1.

3.4.2 The IHU shall not send any message to the EXP1 for a minimum of 10000 milliseconds.

3.4.3 The IHU shall send a Set Run State Standby command message to the EXP1.

3.5 Experiment Power Off Sequence

3.5.1 The IHU shall set the Experiment Enable 1 pin LOW.

3.5.1.1 The absence of a HIGH state on the Experiment Enable 1 pin shall be construed as a LOW state whether the pin is actually LOW, or in a high-impedance state.

4 Message Content Requirements

4.1 Command Message

4.1.1 The message header block shall be constructed as shown in table 2.

4.1.2 The message header block shall be sent with each Command and Response block.

Table 2

Field	Size (Bytes)	Type	Min Value	Max Value	Description
Message Version	2	Unsigned	0x01	0xFFFF	Message ICD version
Software Build	2	Unsigned	0x01	0xFFFF	Software Build version

4.1.2.1 The Message Version shall be an integer representing the IHU to EXP1 ICD document version number from which the message format is derived, having the decimal point removed (e.g. version 1.03 would be 103 decimal or 0x67).

4.1.2.2 The Software Build shall be an integer representing the software build version number of the system originating the message, having any decimal points removed (e.g. version 1.03 would be 103 decimal or 0x67).

4.2 Command Message Block

4.2.1 The command message block shall be constructed as shown in Table 3.

Table 3

Field	Size (Bytes)	Type	Min Value	Max Value	Description
COMMAND	2	Unsigned	0x0000	0x0280	Hexadecimal Command
ARGUMENT	Variable	Unsigned	-	-	Optional Arguments As Required

The command message block shall contain one command in the COMMAND COMMAND field as shown in Table 4.

Table 4

Command Name	Size (Bytes)	Type	Min Value	Max Value	Description
Nop	2	Unsigned	0x0000	0x0000	No effect; response undefined. Test for I²C acknowledgement only.
Echo	2	Unsigned	0x0001	0x0001	Echo this byte stream
Resend	2	Unsigned	0x0002	0x0002	Resend last result
Get UID	2	Unsigned	0x0003	0x0003	Controller 7 byte identifier
Get Status	2	Unsigned	0x0004	0x0004	Controller status indication
Get Diagnostics	2	Unsigned	0x0006	0x0006	Self-check Diagnostic
Get Telemetry	2	Unsigned	0x0010	0x0010	Send telemetry data
Set Run State	2	Unsigned	0x0080	0x0080	Enter specified Run State
Get Run State	2	Unsigned	0x0081	0x0081	Query current Run State
Set Time	2	Unsigned	0x0100	0x0100	Number of seconds since epoch
Get Time	2	Unsigned	0x0101	0x0101	Number of seconds since epoch
Get Data	2	Unsigned	0x0280	0x0280	Send (number of bytes) data

4.2.3 The command message shall contain arguments for the Echo command, as shown in Table 5.

Table 5

Field	Size (Bytes)	Type	Min Value	Max Value	Description
ARGUMENT	4	Unsigned	-	-	Data to be echoed

4.2.4 The command message shall contain one argument for the Set Run State command, as shown in Table 6.

Table 6

Run State	Size (Bytes)	Type	Min Value	Max Value	Description
STANDBY	2	Unsigned	0x01	0x01	Enter Standby State
ACTIVE	2	Unsigned	0x03	0x03	Activate Experiments
HALT	2	Unsigned	0x05	0x05	Terminate Experiments

4.2.5 The command message shall contain arguments for the Set Time command, as shown in Table 7.

Table 7

Argument	Size (Bytes)	Type	Min Value	Max Value	Description
IHU Reset Counter	16	Unsigned	0x00	-	Count of the number of IHU resets from non-volatile FRAM
MET Timestamp	32	Unsigned	-	-	MET timestamp (seconds since last IHU reset)

4.2.6 The command message shall contain arguments for the Get Data command, as shown in Table 8.

Table 8

Argument	Size (Bytes)	Type	Min Value	Max Value	Description
BYTES TO SEND	2	Unsigned	0x00	0xFFFF	Number of bytes to send (1-256)

4.3 Response Message Block

4.3.1 The response message block shall be constructed as shown in Table 9.

Table 9

Field	Size (Bytes)	Type	Min Value	Max Value	Description
RESERVED	1	Unsigned	-	-	Reserved, ignore
ERROR CODE	1	Unsigned	0x0000	0x0006	Response to Command
LENGTH	2	Unsigned	0x00	0xFFFF	Length of Return Value in Bytes
RETURN VALUE	Variable	Variable	-	-	Return Value

4.3.2 The Error Code shall contain one code as shown in table 10.

Table 10

Name	Size (Bytes)	Type	Min Value	Max Value	Description
CMD_OK	1	Unsigned	0x0000	0x0000	Command invoked successfully
CMD_OP_ERR	1	Unsigned	0x0001	0x0001	Command not recognized
CMD_FORMAT_ERR	1	Unsigned	0x0002	0x0002	Incorrect command argument length
CMD_RANGE_ERR	1	Unsigned	0x0003	0x0003	Argument(s) out of bounds
CMD_PEC_ERR	1	Unsigned	0x0004	0x0004	Error check (CRC) mismatch
CMD_EXEC_ERR	1	Unsigned	0x0005	0x0005	Execution error
CMD_VERSION_ERR	1	Unsigned	0x0006	0X0006	Header Message Version mismatch

4.3.3 The Status Flags for a GET STATUS response message shall be represented as individual bit values of a 16 bit RETURN VALUE as shown in Table 11.

Table 11

Name	Bit Number	Description
REBOOTED	0	1 = Experiment has rebooted – **NOT USED**
DATA READY	1	1 = Experiment data available
TIME REQUEST	2	1 = Request SET TIME
FAILED RUN STATE	3	1 = Failed the run state – **NOT USED**
COMPLETED RUN STATE	4	1 = Completed the run state – **NOT USED**
RESERVED	5-15	Always 0

4.3.4 The response message to a Set Time command shall contain one of the values as shown in Table 12.

Table 12

Response Name	Size (Bytes)	Type	Min Value	Max Value	Description
SUCCESS	2	Signed	0x00	0x00	Time Set successfully
FAILURE	2	Signed	0xFFFF	0xFFFF	Time Set failed

5 Message Integrity

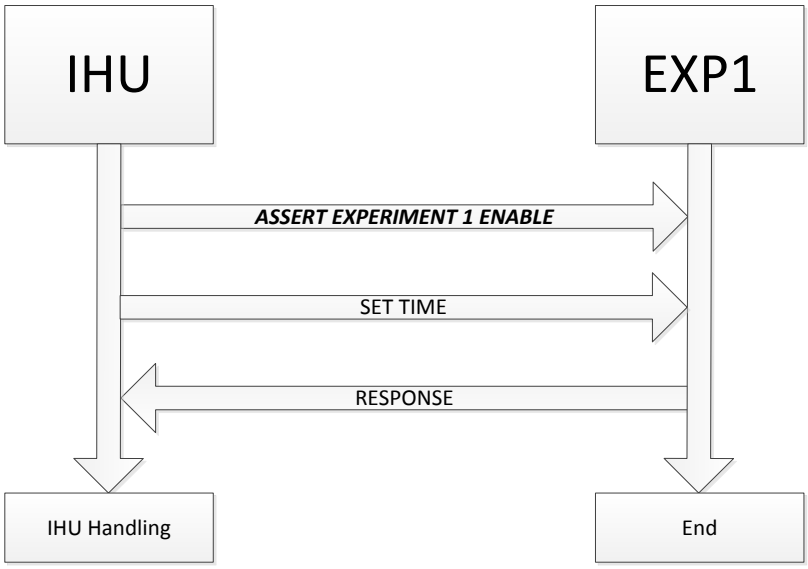
5.1 Invalid Messages

5.1.1 If the PEC (CRC8) fails, the message shall be considered invalid.

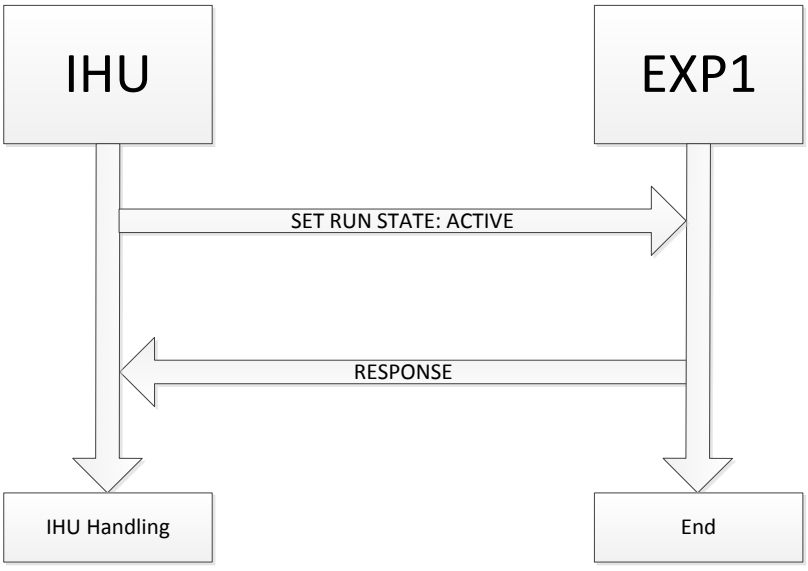
5.1.2 If the Message Version does not match the message version in use for the construction of messages on the receiving system, the message shall be considered invalid.

6 Message Flow Diagrams

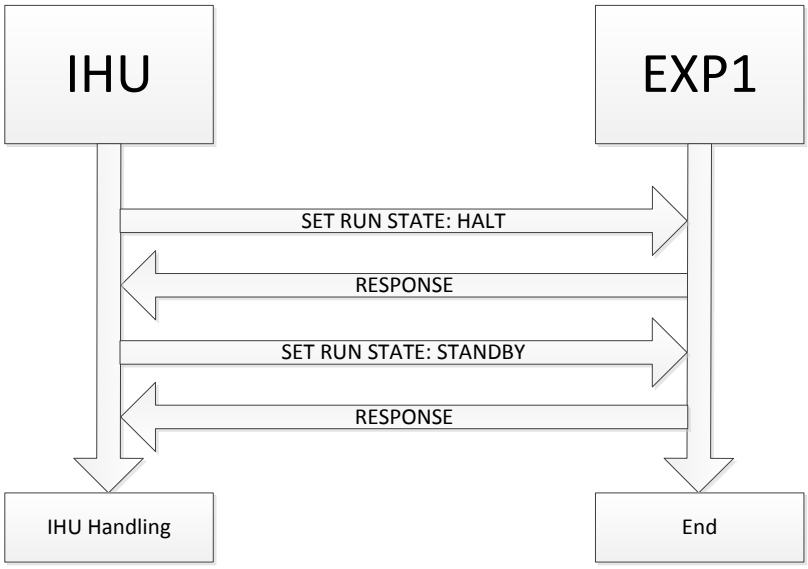
6.1 EXPERIMENT POWER ON SEQUENCE



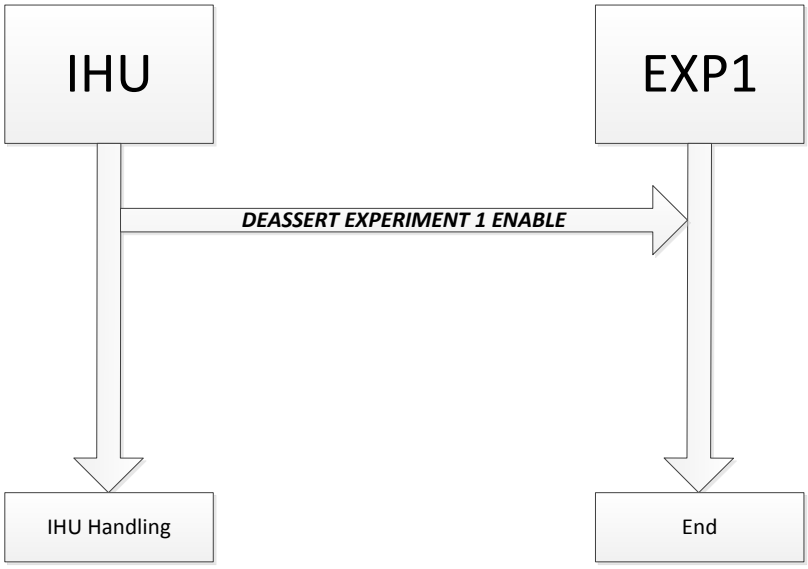
6.2 EXPERIMENT BEGIN OPERATION SEQUENCE



6.3 EXPERIMENT CEASE OPERATION SEQUENCE



6.4 EXPERIMENT POWER OFF SEQUENCE



6.5 SERVICING EXPERIMENT OPERATION

Figure 1

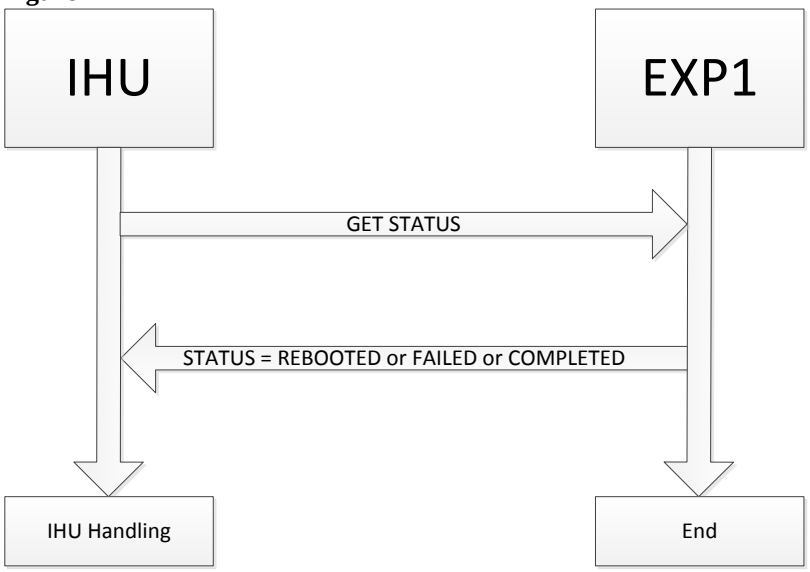


Figure 2

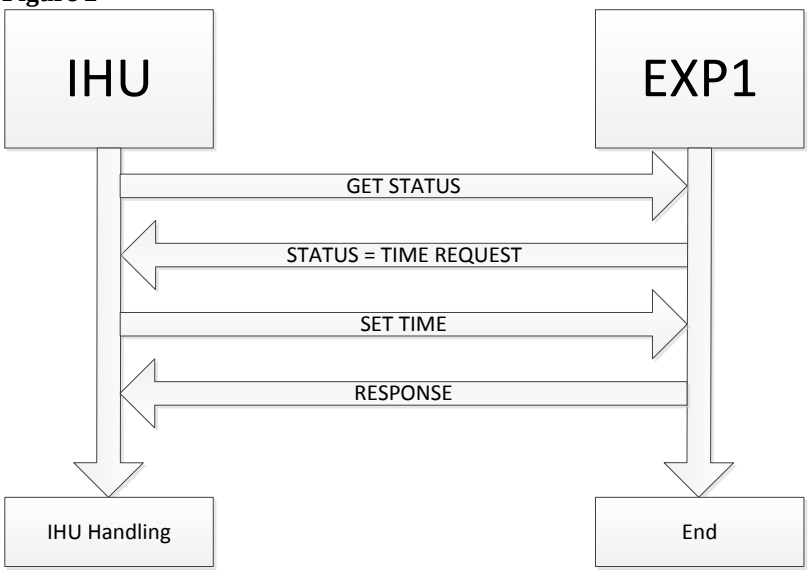
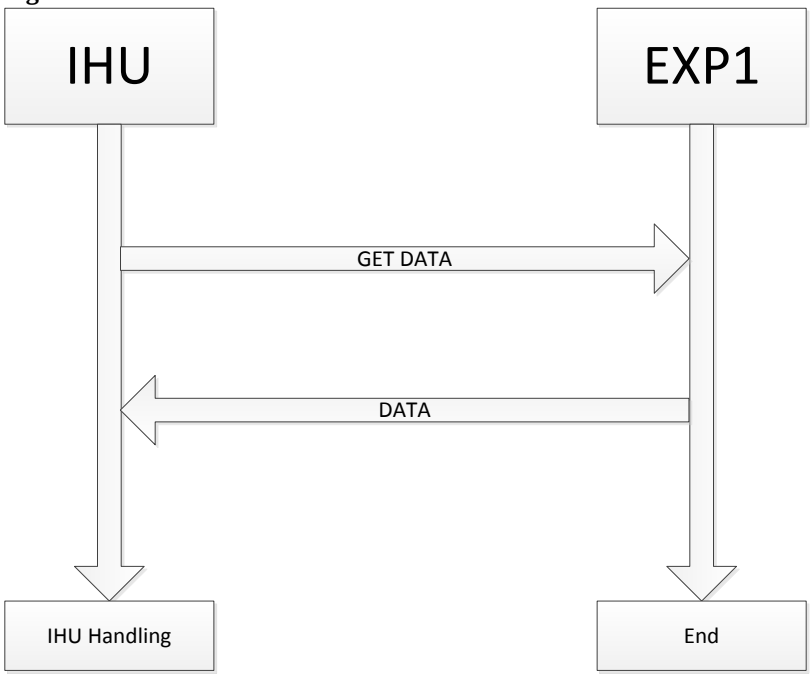


Figure 3



Date: June 26, 2014
Version: Version 1.20

AMSAT *Fox-1A*

IHU to Experiment 4 Interface Control Document

1 Introduction

This document specifies the message interface between the Internal Housekeeping Unit (IHU) and the Experiment System in Position 3 of the satellite, known as the VT Camera Experiment and abbreviated herein as EXP3.

1.1 Document History

DATE	VERSION	SUMMARY
January 24, 2013	1.00	Initial version
February 20, 2013	1.01	Specify byte order as little endian
May 21, 2013	1.10	Update data TYPE names
October 4, 2013	1.11	Change type format to exclude code type, add Min/Max Values, add thermistor circuit
October 7, 2013	1.12	Modify Table 1 to clarify Experiment Enable 4 pin states
June 26, 2014	1.20	Add “No Earth Image Available” to NN description in Table 6, remove section 7 thermistor requirement no longer applicable, change all references to EXP4 to read EXP3 reflecting proper location of experiment

1.2 Document Scope

This document will specify the control of EXP3, the messaging format, and the serial bus hardware operation for the communications between the IHU and the EXP3.

1.3 References

1. AMSAT *Fox-1*, System Requirements Specification
2. AMSAT *Fox-1*, System Design Specification
3. AMSAT *Fox-1*, IHU Software Architecture Specification

2 General Messaging Requirements

2.1 Link Protocol Requirements

2.1.1 The IHU shall initiate a command to the EXP3.

2.1.2 The EXP3 shall send a reply to each IHU request.

2.1.3 Message bit order shall be Little Endian.

2.1.4 The IHU shall determine the action to be taken in the event of an invalid, improper, or missing message from the EXP3.

2.1.5 The EXP3 shall take no action in the event of an invalid or improper message from the IHU.

2.1.6 Message byte order shall be Little Endian.

2.2 General Message Requirements

2.2.1 Each message shall contain a header block.

2.2.2 Each message shall contain one command, one reply, or one data block.

2.3 Serial Bus Hardware Interface Requirements

2.3.1 The bus levels shall be 3.0V.

2.3.2 The bus data speed shall be 38400 bit/s.

2.3.3 The serial bus communication shall be asynchronous.

2.3.4 The number of data bits shall be 8.

2.3.5 The number of stop bits shall be 1.

2.3.6 There shall be no parity bit.

3 Experiment Operation

3.1 Experiment Power Control

3.1.1 The IHU shall exert control over the power state of the EXP3 by the Experiment Enable 4 pin on the satellite bus as shown in Table 1.

Table 1

Pin State	Description
High	Power On Experiment
Low or high-impedance	Power Off Experiment

3.1.2 Upon signaling Power On to the EXP3, the IHU shall not send any message to the EXP3 for a minimum of 100 milliseconds.

3.2 Experiment Operation Sequence

3.2.1 Upon Power On the IHU shall determine the state of the EXP3 by sending an Is Camera Ready command message.

3.2.2 The IHU shall not send a Transmit Data Block command message prior to receiving a Camera Ready reply message from the EXP3.

4 Message Content Requirements

4.1 Message Header Block

4.1.1 The message header block shall be constructed as shown in table 2.

4.1.2 The message header block shall be sent with each Command, Reply, and Data block.

Table 2

Field	Size (Bytes)	Type	Min Value	Max Value	Description
Message Version	2	Unsigned	0x01	0xFFFF	Message ICD version
Software Build	2	Unsigned	0x01	0xFFFF	Software Build version

4.1.2.1 The Message Version shall be an integer representing the IHU to EXP3 ICD document version number from which the message format is derived, having the decimal point removed (e.g. version 1.03 would be 103 decimal or 0x67).

4.1.2.2 The Software Build shall be an integer representing the software build version number of the system originating the message, having any decimal points removed (e.g. version 1.03 would be 103 decimal or 0x67).

4.2 Command Message Block

4.2.1 The command message block shall be constructed as shown in Table 3.

Table 3

Field	Size (Bytes)	Type	Min Value	Max Value	Description
COMMAND	2	Alpha	RR TT	RR TT	Command

4.2.2 The command message block shall contain one command in the COMMAND field as shown in Table 4.

Table 4

Command	Description
RR	Is Camera Ready?
TT	Transmit Data Block

4.3 Reply Message Block

4.3.1 The reply message block shall be constructed as shown in Table 5.

Table 5

Field	Size (Bytes)	Type	Min Value	Max Value	Description
REPLY	2	Alpha	NN YY FF	NN YY FF	Reply

4.3.2 The reply message block shall contain one reply in the REPLY field as shown in table 6.

Table 6

Command	Description
NN	Camera Not Ready or No Earth Image Available
YY	Camera Ready
FF	Camera Failed

4.4 Message Data Block

4.4.1 The message data block shall be constructed as shown in Table 7.

Table 7

Field	Size (Bytes)	Type	Min Value	Max Value	Description
DESCRIPTOR	2	Unsigned	-	-	Line ID and Payload Length
PAYLOAD	Variable	Unsigned	-	-	Array of (Payload Length) bytes
CHKSUM	2	Unsigned	-	-	16 bit accumulator sum of bytes in HEADER and PAYLOAD

4.4.2 The bits of the message data block DESCRIPTOR bytes shall be constructed as shown in Table 8.

Table 8

Field	Size (Bits)	Type	Min Value	Max Value	Description
Line ID	6	Unsigned	0x01	0x3C	640 x 8 pixel picture line number (1 is top, 60 is bottom)
Payload Length	10	Unsigned	0x01	0x3FF	Total number of bytes in PAYLOAD

4.4.2.1 The Line ID shall compose the 6 MSB and the Payload Length shall compose the 10 LSB.

5 Message Integrity

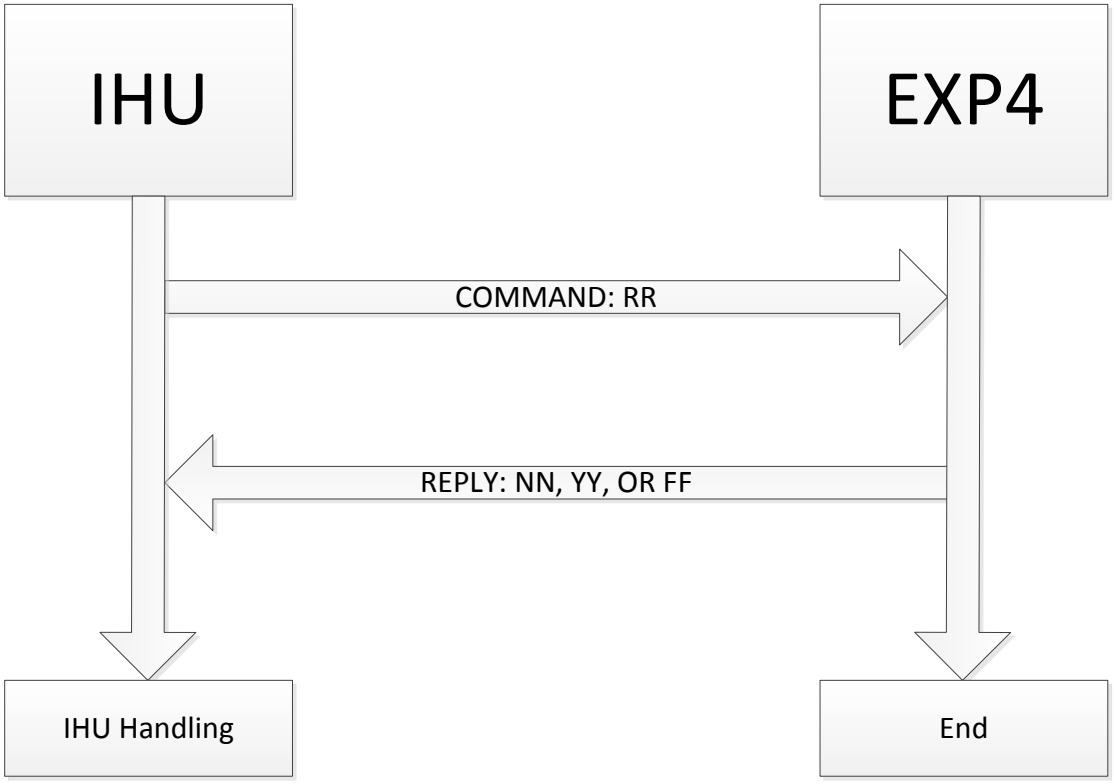
5.1 Invalid Messages

5.1.1 If the DATA block CHKSUM fails, the message shall be considered invalid.

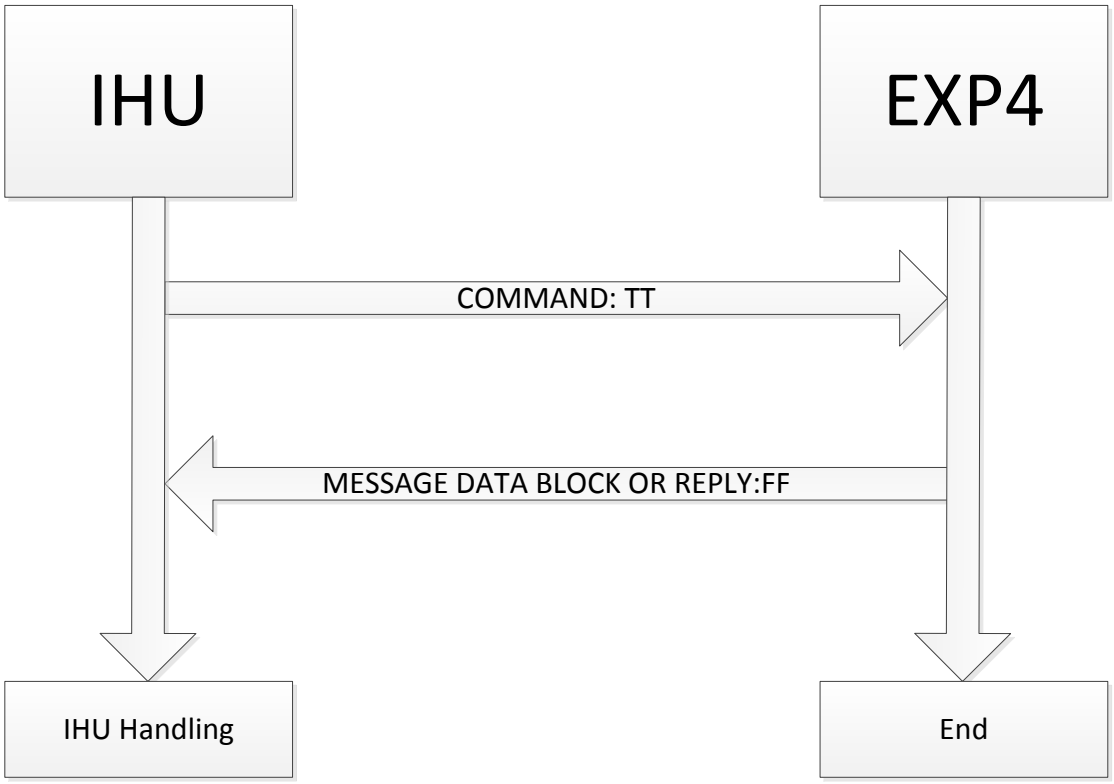
5.1.2 If the Message Version does not match the message version in use for the construction of messages on the receiving system, the message shall be considered invalid.

6 Message Flow Diagrams

6.1 RR COMMAND



6.2 TT COMMAND



Date: May 6, 2015
Version: Version 2.10

AMSAT *Fox-1A*

Downlink Specification

1 Introduction

This document specifies downlink frame formats for the Fox-1A telemetry and experiment telemetry. This specification includes the both slow and high speed formats.

Document History

DATE	VERSION	SUMMARY
April 25, 2013	1.01	Remove TX PA Temperature and TX Osc Temperature, add TX Temperature
May 21, 2013	1.2	High speed downlink details added
May 27, 2013	1.3	Remove Radiation Experiment Telemetry Frame, resize Radiation Experiment Data Frame, renumber Payload Types, added Slow Speed Link Layer Transmission Scheduling, changed Reset Count to 16 bits
June 6, 2013	1.31	Reduce BATT CPU, PSU CPU, IHU CPU, TX Temp, RX Osc Temp from 12 to 8 bit value, add IHU Error Data field to Telemetry Minimum Values Frame
June 26, 2013	1.32	Correct Payload Type numbers in Table 6
August 13, 2013	1.40	Changes due to new BATT telemetry values, delete Type 4 from idle telemetry
August 26, 2013	1.41	Change Receiver Osc Temperature to Receiver Card Temperature, remove TOTAL MPPT I, update 2.2.9.1 and 2.2.9.1.1 to reflect variable size of Radiation Experiment Data available
September 14, 2013	1.42	Added 3.1.2, Payload type 0 debug frame, made Scan Line Segment – Picture Count size 8 bits, add RSSI to Payloads 1, 2, and 3, change type format to exclude code type, add Min/Max Values
September 16, 2013	1.43	Added EXP4 temperature to Payloads 1, 2, and 3, changed PSU CPU temp to PSU card temp

DATE	VERSION	SUMMARY
October 15, 2013	1.44	Correct bit count for frame Type 3, change calculated spin rate to remove PSU reference
November 18, 2013	1.45	Expanded all temperature fields to 12 bits, redo 3.1 payload order, add 2.2.7.3 and 2.2.7.4, update SPIN to show bit pattern, add System I²C Failure indications, add Ground Command TLM reset count, add IHU Soft Error Data, add IHU Hard Error Data, increase IHU Error Data to 32 bits, clarify which fields are raw values, added 2.2.7 5 padding slow speed frames, 2.2.8 for slow speed trailer info
January 13, 2014	1.50	Redo 3.2 beacon payloads
January 13, 2014	1.51	Change 3.2.1 to allow payload type 2 and 3 only with the voice ID
January 13, 2014	1.52	Correct 2.2.9 high speed link layer header structure to show 16 bits on the Reset Count
January 14, 2014	1.53	Correct Table 4 and Table 5 Reset Count Max Value to 0xFFFF to match use of 16 bits
February 10, 2014	1.54	Modify Table 11 to read “Experiment 1 Data” in the description, added Safe Mode Indication bit to payload 2 and 3, changed Filler bit size to 1 in payload 2 and 3.
March 19, 2014	1.55	Move IHU Soft Error Data to Payload Type 3, Move IHU Error Data to Payload Type 1 and rename to IHU Diagnostic Data, update Table 1 Bit Rate to 200 bps and Spectral Efficiency to 2 bps/Hz, remove Scrambler reference from Table 1 and Table 2.
March 24, 2014	1.56	Add timestamp elements to Payload 2 and Payload 3 for specific MAX or MIN last changed
April 23, 2014	1.57	Fix 4.4 BATT Board Temperature description to read Low instead of High
June 10, 2014	1.58	Remove Payload Type 2 MRAM Error Count, Add PSU DC current, PSU DC high current, PSU DC low current to Payload Type 1, 2, 3 respectively
September 30, 2014	2.00	Reorder fields in Payload Type 1, 2, 3, delete filler fields, add filler bits to Table 5

DATE	VERSION	SUMMARY
May 6, 2015	2.10	Revised Payload Type 5 and Picture Data Structure to conform with actual implementation

1.1 Document Scope

The purpose of this document is to specify the downlink protocol on the AMSAT Fox-1A spacecraft.

1.2 References

1. Fox1 IHU to RF ICD
2. Fox1 IHU to Battery ICD
3. Fox1 IHU to PSU ICD
4. Fox1 IHU to Attitude Determination Experiment ICD
5. Fox1 IHU Software Architecture Specification
6. Fox1 IHU to Experiment 1 ICD
7. Fox1 IHU to Experiment 4 ICD

1.3 Definitions

1.3.1 Slow Speed Downlink – Data transmitted at approximately 100 bits per second in the audio portion below 300 Hz simultaneous with the transponder audio.

1.3.2 High Speed Downlink – Data transmitted at approximately 9600 bits per second using the entire downlink audio passband.

1.3.3 Spacecraft Telemetry – Downlink data containing specific information about spacecraft systems and health as defined in the System Requirements and related documents.

1.3.4 Experiment Telemetry – Downlink data containing specific information about the various experiment platforms flown on the satellite.

1.3.5 Frame – A defined set of data with a specific overall size comprised of fields of a specific bit or byte length.

2 Protocol Structure

2.1 Physical Layer

2.1.1 The physical layer includes options for slow-speed and high speed operation.

2.1.2 Slow speed operation uses frequency-shift keying and is transmitted in the sub-audible part of the audio downlink below 300 Hz. It may be transmitted simultaneously with voice or other audio signals. The details of the physical layer are shown in Table 1.

Table 1

Bit Rate	200 bps
Spectral efficiency	2 bps/Hz
Modulation type	Non-coherent Frequency Shift Keying (FSK)
Signal bandwidth	10 Hz to 200 Hz (-3 dB points)
FSK Deviation	500 Hz
Spectral Mask	-20 dB at 300 Hz
RF Channel Bandwidth	1200 Hz

2.1.3 High speed operation uses frequency-shift keying and is transmitted using the entire RF downlink bandwidth. The details of the physical layer are shown in Table 2. *Note that this is the same as the G3RUH modem.*

Table 2

Bit Rate	9600 bps
Spectral efficiency	2 bps/Hz
Modulation type	non-coherent frequency shift keying (FSK)
Signal bandwidth	10 Hz to 4800 Hz (-3 dB points)
FSK Deviation	3 kHz
Spectral Mask	-60 dB at 7500 Hz
RF Channel Bandwidth	20 kHz

2.2 Link Layer

2.2.1 The link layer protocol provides multiplexing, packet identification and forward error correction.

2.2.2 The link layer shall include a header and a trailer surrounding the applications layer payload to form data packets as shown in Table 3.

Table 3

Header	Applications Payload	Trailer

2.2.3 The applications payload layer shall include satellite telemetry, experiment telemetry, high speed data, and debug frames.

2.2.4 Debug frames may be used during ground testing but shall not be transmitted for flight.

2.2.5 Bits shall be transmitted in the order of most significant bit first.

2.2.6 Bytes shall be transmitted in Little Endian order.

2.2.7 The Slow Speed link layer header structure shall be as shown in Table 4.

Table 4

Field	Size (Bits)	Type	Min Value	Max Value	Description
Fox ID	3	Unsigned	0x01	0x01	0x01 specifies Fox-1A (each Fox satellite will have a unique ID)
Reset Count	16	Unsigned	0x00	0xFFFF	Total number of times IHU has reset since initial on-orbit startup
Uptime	25	Unsigned	0x00	0x1FFFFFF	This is the IHU uptime in seconds since the last reset
Type	4	Unsigned	0x00	0x0F	This identifies the payload type

2.2.7.1 Payload type shall be as specified in the application layer payload data.

2.2.7.2 Each Slow Speed link layer structure shall contain only one payload type.

2.2.7.3 Reset Count and Uptime shall reflect the time at which the payload data was collected.

2.2.7.4 Reset Count and Uptime shall not be changed if the payload data has not been updated.

2.2.7.5 Real-Time Telemetry Frame, Telemetry Maximum Values Frame, and Telemetry Minimum Values Frame data shall be padded with zeros to equal 58 bytes length for each.

2.2.8 Forward error correction (FEC) code words shall be sent in the link layer trailer. The FEC shall be a Reed Solomon RS 255,223 code. (This provides 32 parity bytes per code word allowing error detection and correction capability.)

2.2.9 The High Speed link layer header structure is shown in Table 5.

Table 5

Field	Size (Bits)	Type	Min Value	Max Value	Description
Fox ID	3	Unsigned	0x01	0x01	0x01 specifies Fox-1A (each Fox satellite will have a unique ID)
Reset Count	16	Unsigned	0x00	0xFFFF	Total number of times IHU has reset since initial on-orbit startup
Uptime	25	Unsigned	0x00	0x1FFFFFF	This is the IHU uptime in seconds since the last reset
(No Value)	4	Unsigned	0x00	0x00	4 bit filler

2.2.10 The High Speed link layer applications payload shall contain data from all payload types, as shown in table 6.

Table 6

Payload Type	Size (Bytes)	Description
1	60	Real-Time Telemetry Frame
2	60	Telemetry Maximum Values Frame
3	60	Telemetry Minimum Values Frame
5	Variable 1 - 4300	Camera JPEG Data Frame
4	58	Radiation Experiment High Speed Data Frame

2.2.10.1 A varying number of Radiation Experiment Data bytes shall be sent to fill the applications payload size to a total of 4600 bytes if the payload type 5 data is less than 4300 bytes.

2.2.10.1.1 When less than a sufficient number of bytes to contain a useful data frame remain to fill to 4600 bytes, the remaining bytes shall be filled with zeros.

2.2.10.2 Real-Time Telemetry Frame, Telemetry Maximum Values Frame, and Telemetry Minimum Values Frame data shall be padded with zeros to equal 60 bytes length for each.

2.2.11 Forward error correction (FEC) code words shall be sent in the link layer trailer. The FEC shall be a Reed Solomon RS 255,223 code. (This provides 32 parity bytes per code word allowing error detection and correction capability.) Twenty one code words will be populated in parallel, with 1 byte being added to each code word in sequence until all

bytes have been processed. The last code word will be partially filled and should be virtually padded with 77 bytes. The data will then be sent sequentially with 8b10b coding. Twenty one sets of 32 parity bytes will follow after all data has been sent for the high speed frame.

3 Slow Speed Link Layer Transmission Scheduling

3.1 While IHU PTT is asserted Payload Types contained in the Link Layer Applications Payload shall rotate, changing type with each successive link layer transmitted, in the following order:

- Type 1
- Type 4
- Type 4
- Type 1
- Type 4
- Type 4
- Type 1
- Type 4
- Type 4
- Type 1
- Type 2
- Type 4
- Type 1
- Type 4
- Type 4
- Type 1
- Type 4
- Type 4
- Type 1
- Type 4
- Type 4
- Type 1
- Type 3
- Type 4

3.1.1 The above order shall be repeated so long as IHU PTT is asserted.

3.1.2 Each time IHU PTT is asserted the order shall begin at the top.

3.1.3 The IHU PTT shall not be de-asserted during transmission of a Link Layer.

3.2 While beacon message is sent during idle timer expired the Payload Types contained in the Link Layer Applications Payload shall be transmitted in alternating sets, one set per beacon message:

Set 1:
- Type 1
- Type 2

Set 2:
- Type 1
- Type 3

3.2.1 The payload type 2 or 3 data shall be sent simultaneously with the voice ID.

4 Application Layer Payload Data

4.1 Payload Type 0 – Debug Frame (NOT TO BE TRANSMITTED FOR FLIGHT)

Table 7

Field	Size (Bits)	Type	Min Value	Max Value	Description
UNDEFINED	1 - 464	Undefined	-	-	Debug data for ground testing

4.2 Payload Type 1 - Real-Time Telemetry Frame (Size = 429 bits)

Table 8

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
BATT A V	12	Unsigned	0x00	0xFFF	Battery pair A voltage raw value (0-2.5V scale)	0
BATT B V	12	Unsigned	0x00	0xFFF	Battery pairs A+B voltage raw value (0-3.3V scale)	12
BATT C V	12	Unsigned	0x00	0xFFF	Battery pairs A+B+C voltage raw value (0-5.0V scale) This value also represents the power bus voltage (VBATT)	24
BATT A T	12	Unsigned	0x00	0xFFF	Battery pair A temperature raw value	36
BATT B T	12	Unsigned	0x00	0xFFF	Battery pair B temperature raw value	48
BATT C T	12	Unsigned	0x00	0xFFF	Battery pair C temperature raw value	60
TOTAL BATT I	12	Signed	0x00	0xFFF	Total Battery DC current raw value	72
BATT Board Temperature	12	Unsigned	0x00	0xFFF	PC Board Temperature of BATT raw value	84
+X PANEL V	12	Unsigned	0x00	0xFFF	+X solar panel voltage raw value	96
-X PANEL V	12	Unsigned	0x00	0xFFF	-X solar panel voltage raw value	108
+Y PANEL V	12	Unsigned	0x00	0xFFF	+Y solar panel voltage raw value	120
-Y PANEL V	12	Unsigned	0x00	0xFFF	-Y solar panel voltage raw value	132
+Z PANEL V	12	Unsigned	0x00	0xFFF	+Z solar panel voltage raw value	144
-Z PANEL V	12	Unsigned	0x00	0xFFF	-Z solar panel voltage raw value	156
+X PANEL T	12	Unsigned	0x00	0xFFF	+X solar panel temperature raw value	168
-X PANEL T	12	Unsigned	0x00	0xFFF	-X solar panel temperature raw value	180
+Y PANEL T	12	Unsigned	0x00	0xFFF	+Y solar panel temperature raw value	192
-Y PANEL T	12	Unsigned	0x00	0xFFF	-Y solar panel temperature raw value	204
+Z PANEL T	12	Unsigned	0x00	0xFFF	+Z solar panel temperature raw value	216

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
-Z PANEL T	12	Unsigned	0x00	0xFFF	-Z solar panel temperature raw value	228
PSU Temperature	12	Unsigned	0x00	0xFFF	PSU card temperature raw value	240
SPIN	12	Signed	0x00	0xFFF	Calculated spin rate RPM using solar cells Bit 11 = sign Bits 10 to 8 = integer Bits 7 to 0 = fraction	252
TX PA Current	12	Unsigned	0x00	0xFFF	Transmit power amplifier current raw value	264
TX Temperature	12	Unsigned	0x00	0xFFF	Transmitter card temperature raw value	276
RX Temperature	12	Unsigned	0x00	0xFFF	Receiver card temperature raw value	288
RSSI	12	Unsigned	0x00	0xFFF	Received Signal Strength Indication raw value	300
IHU CPU Temperature	12	Unsigned	0x00	0xFFF	CPU Temperature of IHU raw value	312
Satellite X Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Raw Angle	324
Satellite Y Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Raw Angle	336
Satellite Z Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Raw Angle	348
EXP 4 Temperature	12	Unsigned	0x00	0xFFF	Experiment 4 card temperature raw value	360
PSU Current	12	Unsigned	0x00	0xFFF	PSU DC current	372
IHU Diagnostic Data	32	Unsigned	-	-	Diagnostic Data on IHU Performance	384
Experiment Failure Indication	4	Unsigned	0x00 0x08	0x01 0x09	Bit 0 is Experiment 1 Bit 1 is Experiment 2 (N/A on Fox-1A) Bit 2 is Experiment 3 (N/A on Fox-1A) Bit 3 is Experiment 4 State: 0 = Working, 1 = Failed	416

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
System I2C Failure Indications	3	Unsigned	0x00	0x07	Bit 0 is BATT Bit 1 is PSU Device 1 Bit 2 is PSU Device 2 State: 0 = Working, 1 = Failed	420
Number of Ground Commanded TLM Resets	4	Unsigned	0x00	0x0F	Number of times command stations reset stored telemetry	423
Antenna Deploy Sensors	2	Unsigned	0x00	0x03	Bit 0 is RCV Bit 1 is XMT State: 0 = stowed 1 = deployed	427

4.3 Payload Type 2 - Telemetry Maximum Values Frame (Size = 460 bits)

Table 9

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
BATT A V	12	Unsigned	0x00	0xFFF	Battery pair A high voltage raw value (0-2.5V scale)	0
BATT B V	12	Unsigned	0x00	0xFFF	Battery pairs A+B high voltage raw value (0-3.3V scale)	12
BATT C V	12	Unsigned	0x00	0xFFF	Battery pairs A+B+C high voltage raw value (0-5.0V scale) This value also represents the power bus voltage (VBATT)	24
BATT A T	12	Unsigned	0x00	0xFFF	Battery pair A high temperature raw value	36
BATT B T	12	Unsigned	0x00	0xFFF	Battery pair B high temperature raw value	48
BATT C T	12	Unsigned	0x00	0xFFF	Battery pair C high temperature raw value	60
TOTAL BATT I	12	Signed	0x00	0xFFF	Battery DC high current raw value	72
BATT Board Temperature	12	Unsigned	0x00	0xFFF	High PC Board Temperature of BATT raw value	84
+X PANEL V	12	Unsigned	0x00	0xFFF	+X solar panel high voltage raw value	96
-X PANEL V	12	Unsigned	0x00	0xFFF	-X solar panel high voltage raw value	108
+Y PANEL V	12	Unsigned	0x00	0xFFF	+Y solar panel high voltage raw value	120
-Y PANEL V	12	Unsigned	0x00	0xFFF	-Y solar panel high voltage raw value	132
+Z PANEL V	12	Unsigned	0x00	0xFFF	+Z solar panel high voltage raw value	144
-Z PANEL V	12	Unsigned	0x00	0xFFF	-Z solar panel high voltage raw value	156
+X PANEL T	12	Unsigned	0x00	0xFFF	+X solar panel high temperature raw value	168

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
-X PANEL T	12	Unsigned	0x00	0xFFF	-X solar panel high temperature raw value	180
+Y PANEL T	12	Unsigned	0x00	0xFFF	+Y solar panel high temperature raw value	192
-Y PANEL T	12	Unsigned	0x00	0xFFF	-Y solar panel high temperature raw value	204
+Z PANEL T	12	Unsigned	0x00	0xFFF	+Z solar panel high temperature raw value	216
-Z PANEL T	12	Unsigned	0x00	0xFFF	-Z solar panel high temperature raw value	228
PSU Temperature	12	Unsigned	0x00	0xFFF	PSU card high temperature raw value	240
SPIN	12	Signed	0x00	0xFFF	Highest calculated spin rate RPM using solar cells	252
TX PA Current	12	Unsigned	0x00	0xFFF	Transmit power amplifier high current raw value	264
TX Temperature	12	Unsigned	0x00	0xFFF	Transmitter card high temperature raw value	276
RX Temperature	12	Unsigned	0x00	0xFFF	Receiver card high temperature raw value	288
RSSI	12	Unsigned	0x00	0xFFF	High Received Signal Strength Indication raw value	300
IHU CPU Temperature	12	Unsigned	0x00	0xFFF	High CPU Temperature of IHU raw value	312
Satellite X Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Highest Raw Angle	324
Satellite Y Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Highest Raw Angle	336
Satellite Z Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Highest Raw Angle	348

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
EXP 4 Temperature	12	Unsigned	0x00	0xFFF	Experiment 4 card high temperature raw value	360
PSU Current	12	Unsigned	0x00	0xFFF	PSU DC high current	372
IHU Hard Error Data	32	Unsigned	-	-	Diagnostic Data on IHU Hard Errors	384
MAX Timestamp Reset Count	16	Unsigned	0x00	0xFFFF	At last MAX, total number of times IHU has reset since initial on-orbit startup	416
MAX Timestamp Uptime	25	Unsigned	0x00	0x1FFFFFF	At last MAX, the IHU uptime in seconds since the last reset	432
Safe Mode Indication	1	Unsigned	0x00	0x01	State: 1 = Safe Mode Active	457
Auto-Safe Mode Indication	1	Unsigned	0x00	0x01	State: 1 = Safe Mode activated by Auto-Safe	458
Auto-Safe Enabled	1	Unsigned	0x00	0x01	State: 1 = Auto-Safe Mode enabled	459

4.4 Payload Type 3 - Telemetry Minimum Values Frame (Size = 460 bits)

Table 10

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
BATT A V	12	Unsigned	0x00	0xFFF	Battery pair A low voltage raw value (0-2.5V scale)	0
BATT B V	12	Unsigned	0x00	0xFFF	Battery pair A+B low voltage raw value (0-3.3V scale)	12
BATT C V	12	Unsigned	0x00	0xFFF	Battery pair A+B+C low voltage raw value (0-5.0V scale) This value also represents the power bus voltage (VBATT)	24
BATT A T	12	Unsigned	0x00	0xFFF	Battery pair A low temperature raw value	36
BATT B T	12	Unsigned	0x00	0xFFF	Battery pair B low temperature raw value	48
BATT C T	12	Unsigned	0x00	0xFFF	Battery pair C low temperature raw value	60
TOTAL BATT I	12	Signed	0x00	0xFFF	Battery DC low current raw value	72
BATT Board Temperature	12	Unsigned	0x00	0xFFF	Low PC Board Temperature of BATT raw value	84
+X PANEL V	12	Unsigned	0x00	0xFFF	+X solar panel low voltage raw value	96
-X PANEL V	12	Unsigned	0x00	0xFFF	-X solar panel low voltage raw value	108
+Y PANEL V	12	Unsigned	0x00	0xFFF	+Y solar panel low voltage raw value	120
-Y PANEL V	12	Unsigned	0x00	0xFFF	-Y solar panel low voltage raw value	132
+Z PANEL V	12	Unsigned	0x00	0xFFF	+Z solar panel low voltage raw value	144
-Z PANEL V	12	Unsigned	0x00	0xFFF	-Z solar panel low voltage raw value	156
+X PANEL T	12	Unsigned	0x00	0xFFF	+X solar panel low temperature raw value	168

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
-X PANEL T	12	Unsigned	0x00	0xFFF	-X solar panel low temperature raw value	180
+Y PANEL T	12	Unsigned	0x00	0xFFF	+Y solar panel low temperature raw value	192
-Y PANEL T	12	Unsigned	0x00	0xFFF	-Y solar panel low temperature raw value	204
+Z PANEL T	12	Unsigned	0x00	0xFFF	+Z solar panel low temperature raw value	216
-Z PANEL T	12	Unsigned	0x00	0xFFF	-Z solar panel low temperature raw value	228
PSU Temperature	12	Unsigned	0x00	0xFFF	PSU card low temperature raw value	240
SPIN	12	Signed	0x00	0xFFF	Lowest calculated spin rate RPM using solar cells	252
TX PA Current	12	Unsigned	0x00	0xFFF	Transmit power amplifier low current raw value	264
TX Temperature	12	Unsigned	0x00	0xFFF	Transmitter card low temperature raw value	276
RX Temperature	12	Unsigned	0x00	0xFFF	Receiver card low temperature raw value	288
RSSI	12	Unsigned	0x00	0xFFF	Low Received Signal Strength Indication raw value	300
IHU CPU Temperature	12	Unsigned	0x00	0xFFF	Low CPU Temperature of IHU raw value	312
Satellite X Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Lowest Raw Angle	324
Satellite Y Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Lowest Raw Angle	336
Satellite Z Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Lowest Raw Angle	348

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
EXP 4 Temperature	12	Unsigned	0x00	0xFFF	Experiment 4 card low temperature raw value	360
PSU Current	12	Unsigned	0x00	0xFFF	PSU DC low current	372
IHU Soft Error Data	32	Unsigned	-	-	Diagnostic Data on IHU Soft Errors	384
MIN Timestamp Reset Count	16	Unsigned	0x00	0xFFFF	At last MIN, total number of times IHU has reset since initial on-orbit startup	416
MIN Timestamp Uptime	25	Unsigned	0x00	0x1FFFFFF	At last MIN, the IHU uptime in seconds since the last reset	432
Safe Mode Indication	1	Unsigned	0x00	0x01	State: 1 = Safe Mode Active	457
Auto-Safe Mode Indication	1	Unsigned	0x00	0x01	State: 1 = Safe Mode activated by Auto-Safe	458
Auto-Safe Enabled	1	Unsigned	0x00	0x01	State: 1 = Auto-Safe Mode enabled	459

4.5 Payload Type 4 - Radiation Experiment Data Frame (Size = 464 bits)

Table 11

Field	Size (Bytes)	Type	Min Value	Max Value	Description
Data	58	Unsigned	-	-	Experiment 1 Data

4.6 Payload Type 5 - Camera JPEG Data Frame (Size is variable)

Table 12

Field	Size (Bits)	Type	Min Value	Max Value	Description
Scan Line Count	8	Unsigned	0x00	0xFF	Count of scan lines in payload
Picture Data	Variable	Unsigned	--	--	Picture Data Structure (Section 5)

5 Picture Data Structure

5.1 Scan Line Segment

Table 13

Field	Size (Bits)	Type	Min Value	Max Value	Description
Picture Counter	8	Unsigned	0x00	0xFF	Picture count indicator
Scan Line Number	6	Unsigned	0x00	0x3B	0x00 = top scan line
Scan Line Length	10	Unsigned	0x001	0x3FF	Count of bytes in the scan line
Scan Line Data	Variable	Unsigned	-	-	(Fragment Length) Scan Line Data

5.1.1 Total Scan Line Segment data size for one Applications Payload frame shall not exceed 4299 bytes.

Date: February 21, 2015
Version: Version 1.04

AMSAT *Fox-1D*

IHU to Experiment 1 Interface Control Document

1 Introduction

This document specifies the message interface between the Internal Housekeeping Unit (IHU) and the University of Iowa Experiment System, EXP 1 of the satellite, known as the High-Energy Radiation CubeSat Instrument and abbreviated as HERCI.

1.1 Document History

DATE	VERSION	SUMMARY
November 13, 2014	0.5	Draft version
November 14, 2014	0.6	Draft update
November 30, 2014	0.6	Draft update #2
December 2, 2014	0.7	Changed source template to reflect SPI, replaced EXP4 with EXP1
December 2, 2014	0.7	Changed CAMERA to DETECTOR (provisional) throughout and added "No Detector Data Available" reply in Table 6
December 15, 2014	0.8	Incorporated changes from U of I, renamed EXP to HERCI, etc..
January 1, 2015	0.81	Changed Experiment Enable 4 to Experiment Enable 1
January 9, 2015	0.9	Added CLOCK field to Table 3, added STATUS field to Table 5, CUT LINE ID from Table 7, 8
January 14, 2015	0.91	Added HOUSEKEEPING to op sequence, HK, EE (provisional) to command message block and flow diagrams.
January 19, 2015	0.92	Cut 4.4.2 – LINE ID + Length descriptor bits
January 22, 2015	0.95	Changed Reply to Failure
February 10, 2015	0.97	Swapped CLOCK field in favor of separate time fields, temp add "PP" command
February 13, 2015	0.98	Cleaned up formatting, added ZZ command, diagram, expanded on STATUS codes
February 13, 2015	0.99	Added RR command text & flows, added DD message block, Power On sequence flows, added draft power cycle criteria.
February 16, 2015	1.00	Revised message header, added Safe Mode exception to Power Off sequence, added ICD version code (later removed).
February 17, 2015	1.01	Added subrequirements for compound cases.
February 17, 2015	1.02	Deleted text from Power On diagram.
February 19, 2015	1.03	Deleted DD and EE commands, deleted STATUS code. Cleaned up formatting.
February 21, 2015	1.04	Changed bus voltage to 3.3 (based on email thread), reordered message header information for clarity, reformatted, renumbered.

1.2 Document Scope

This document will specify the control of HERCI, the messaging format, and the serial bus hardware operation for the communications between the IHU and HERCI.

References

1. AMSAT *Fox-1,* System Requirements Specification
2. AMSAT *Fox-1*, System Design Specification
3. AMSAT *Fox-1*, IHU Software Architecture Specification

2 General Messaging Requirements

2.1 Link Protocol Requirements

2.1.1 The IHU shall initiate a command to HERCI.

2.1.2 HERCI shall send a reply to each IHU request.

2.1.3 Message bit order shall be least significant bit first.

2.1.4 The IHU shall determine the action to be taken in the event of an invalid, improper, or missing message from the HERCI.

2.1.5 HERCI shall take no action in the event of an invalid or improper message from the IHU.

2.1.6 Message byte order shall be Little Endian.

2.2 General Message Requirements

2.2.1 Each message shall contain a header block.

2.2.2 Each message shall contain one command, one reply, or one data block.

2.3 Serial Bus Hardware Interface Requirements

2.3.1 The bus levels shall be 3.3V.

2.3.2 The bus data speed shall be 38400 bit/s.

2.3.3 The serial bus communication shall be asynchronous.

2.3.4 The number of data bits shall be 8.

2.3.5 The number of stop bits shall be 1.

2.3.6 There shall be no parity bit.

3 Experiment Operation

3.1 Experiment Power Control

3.1.1 The IHU shall exert control over the power state of HERCI by the Experiment Enable 1 pin on the satellite bus as shown in Table 1.

Table 1

Pin State	Description
High	Power On Experiment
Low or high-impedance	Power Off Experiment

3.1.2 Upon signaling Power On to HERCI, the IHU shall not power down HERCI for a minimum of 90 seconds

3.1.2.1 If the satellite is commanded into Safe Mode during the 90 second interval, the IHU shall not wait for the remainder of the interval before signaling Power Off.

3.1.3 Upon signaling Power On to HERCI, IHU will wait up to 45 seconds for an unsolicited FF reply message block, indicating HERCI has failed self-test. After waiting the 45 seconds, IHU will send HH housekeeping request messages every 10 seconds for an additional 50 seconds. If HERCI does not respond to one of those HH request messages with a housekeeping data reply message, HERCI shall be considered failed and the IHU shall perform the following Power Cycle Sequence:

3.1.3.1 The IHU shall signal Power Off to HERCI.

3.1.3.2 The IHU shall wait 30 seconds.

3.1.3.3 The IHU shall signal Power On to HERCI.

3.1.3.4 The IHU shall perform this Power Cycle (3.1.3.1 to 3.1.3.3) up to three total cycles.

3.1.3.5 This state shall be reset when the IHU is reset (power cycle) and HERCI will be powered up again using the cycle in 3.1.3.1 to 3.1.3.4.

3.1.4 If at any time after 90 seconds following Power On HERCI exhibits any of the following behaviors, the IHU shall perform a Power Cycle Sequence.

3.1.4.1 Failure to respond to three consecutive Data Block commands.

3.1.4.2 DETECTOR Not Ready (NN) responses to three consecutive Data Block commands.

3.1.4.3 DETECTOR Failed (FF) responses to three consecutive Data Block commands.

3.1.5 When entering Safe Mode, the IHU shall perform the following actions:

3.1.5.1 The IHU shall send a Safe Mode Notification command to HERCI.

3.1.5.2 The IHU shall wait 5 seconds.

3.1.5.3 The IHU will signal Power Off to HERCI.

3.2 Experiment Operation Sequence

3.2.1 The IHU shall request housekeeping telemetry by sending a Transmit HOUSEKEEPING Data Block command message at least once every 30 seconds while in transponder mode, but no more than once every 10 seconds.

3.2.2 The IHU shall send updated time in the CLOCK fields of each command message.

4 Message Content Requirements

4.1 Message Header Block

4.1.1 The message header block shall be constructed as shown in table 2.

4.1.2 The message header block shall precede each command message.

Table 2

Field	Size (Bytes)	Type	Min Value	Max Value	Description
Message Version	2	Unsigned	0x01	0xFFFF	Message ICD version
Software Build	2	Unsigned	0x01	0xFFFF	Software Build version

4.1.2.1 The Message Version shall be an integer representing the IHU to HERCI ICD document version number from which the message format is derived, having the decimal point removed (e.g. version 1.03 would be 103 decimal or 0x67.

4.1.2.2 The Software Build shall be an integer representing the software build version number of the system originating the message, having any decimal points removed (e.g. version 1.03 would be 103 decimal or 0x67).

4.2 Reply Message Block

4.2.1 The Reply Message block shall be constructed as shown in Table 3.

4.2.2 The Reply Message Block shall precede each command message.

Table 3

Field	Size (Bytes)	Type	Min Value	Max Value	Description
MESSAGE VERSION	2	Unsigned	0x01	0xFFFF	Message ICD version
SOFTWARE BUILD	2	Unsigned	0x01	0xFFFF	Software Build version
REPLY CODE	2	Alpha	YY NN FF UU	YY NN FF UU	REPLY CODE
PAYLOAD SIZE	2	Unsigned	0x00	0xFFFF	Number of bytes following this reply message block

4.2.2.1 The Message Version shall be an integer representing the IHU to HERCI ICD document version number from which the message format is derived, having the decimal point removed (e.g. version 1.03 would be 103 decimal or 0x67).

4.2.2.2 The Software Build shall be an integer representing the software build version number of the system originating the message, having any decimal points removed (e.g. version 1.03 would be 103 decimal or 0x67).

4.2.2.3 The Reply Message block shall contain one REPLY CODE in the REPLY CODE field as shown in table 4.

Table 4

Reply Code	Description
NN	DETECTOR Not Ready or No Detector Data Available
FF	DETECTOR Failed
YY	EE, ZZ Command message acknowledged
UU	Message from IHU unexpected or otherwise malformed

4.3 Command Message Block

4.3.1 The command message block shall be constructed as shown in Table 5.

Table 5

Field	Size (Bytes)	Type	Min Value	Max Value	Description
COMMAND	2	Alpha	HH PP RR ZZ	HH PP RR ZZ	Command
RESET COUNT	2	Unsigned	0x00	0xFFFF	Total number of times IHU has reset since initial on-orbit startup
UPTIME WHOLE SECONDS	4	Unsigned	0x0000	0xFFFFFFFF	Uptime in seconds since the last IHU reset
UPTIME FRACTIONAL SECONDS	2	Unsigned	0x0000	0xFFFF	This is the fractional seconds since the last IHU reset. (**Note:** this value may be slightly delayed based on its position in the task queue)
CHECKSUM	2	Unsigned	0x0000	0xFFFF	16 bit rollover accumulator

4.3.2 The command message block shall contain one command in the COMMAND field as shown in Table 6.

Table 6

Command	Description
HH	Transmit HOUSEKEEPING Data Block
PP	Transmit PACKET (of DETECTOR) Data Block
RR	RESEND previous PACKET Data Block
ZZ	Safe Mode Notification

4.4 Message Data Block

4.4.1 The message data block for HOUSEKEEPING and PACKET Data Blocks shall be constructed as shown in Table 7.

Table 7

Field	Size (Bytes)	Type	Min Value	Max Value	Description
TYPE	2	Alpha	DD HH	DD HH	Data or Housekeeping Data Block
PAYLOAD	Variable - max of 58 bytes for Housekeeping, 868 bytes for Detector Data	Unsigned	-	-	Payload
CHKSUM	2	Unsigned	0x00	0xFFFF	16 bit rollover accumulator sum of bytes in HEADER and PAYLOAD

5 Message Integrity

5.1 Invalid Messages

5.1.1 If the DATA block CHKSUM fails in a response to a Transmit HOUSEKEEPING Data Block command, the message shall be considered invalid.

5.1.2 If the Message Version does not match the message version in use for the construction of messages on the receiving system, the message shall be considered invalid.

5.1.3 The IHU shall consider a UU response an “invalid” message.

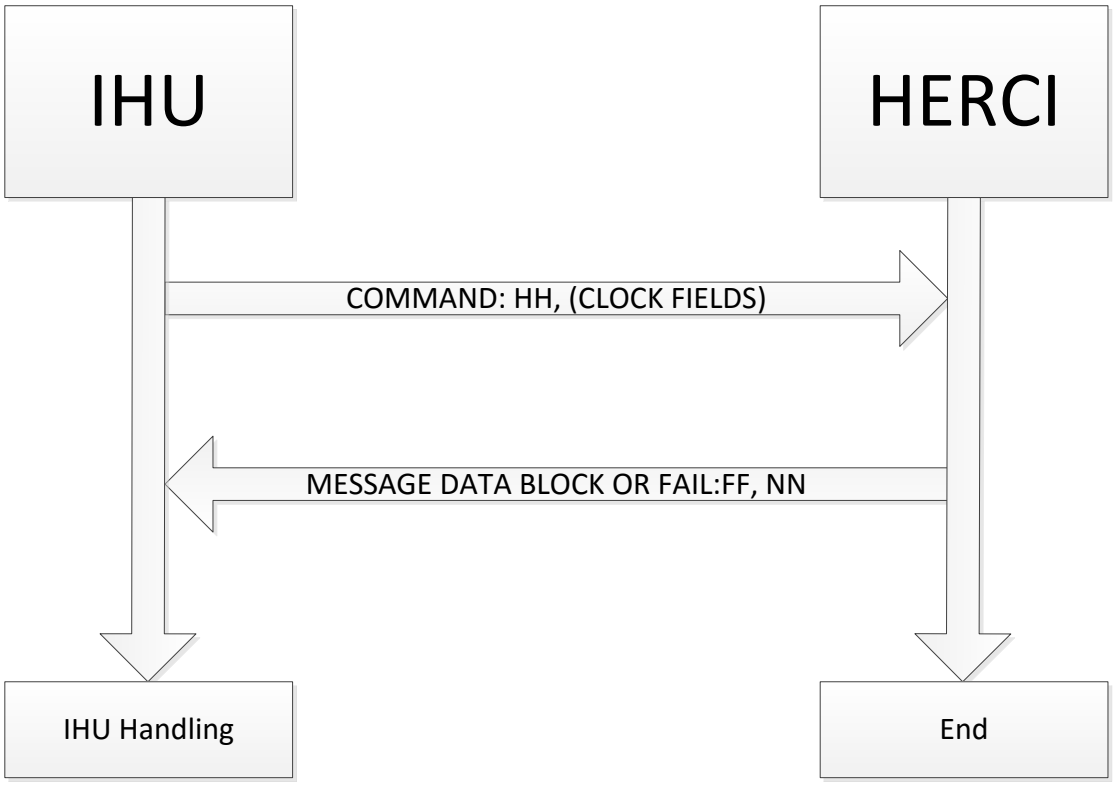
5.1.4 In the event of 3 consecutive invalid messages, the IHU shall power cycle HERCI as described in 3.1.3.1 to 3.1.3.4

5.1.5 If the DATA block CHKSUM fails in a response to a Transmit Packet Data Block command, the IHU shall send a Resend Packet command. After 3 consecutive failed responses to a PP or RR command, the IHU shall power cycle HERCI as described in 3.1.3.1 – 3.1.3.4

6 Message Flow Diagrams

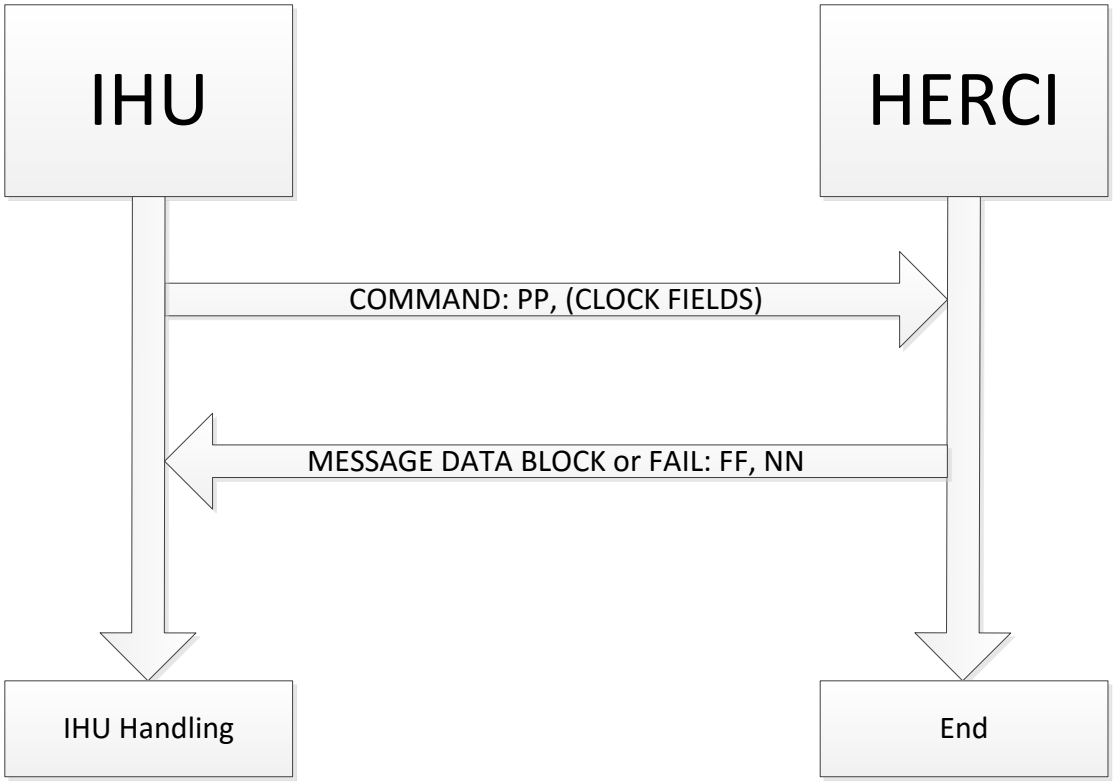
6.1 HH COMMAND

HERCI responds to the HH command by returning a housekeeping record embedded in the response. HH command may occur at any time.



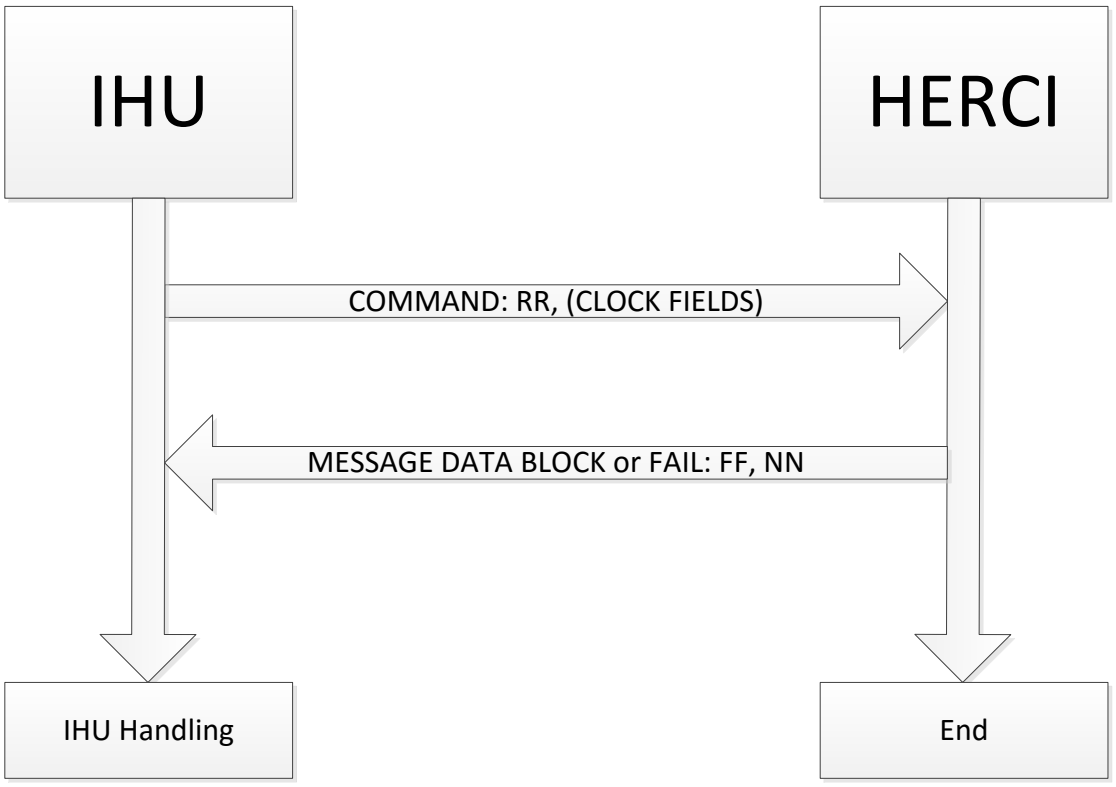
6.2 PP COMMAND

HERCI responds to the PP command by returning a telemetry transport frame embedded in the response.



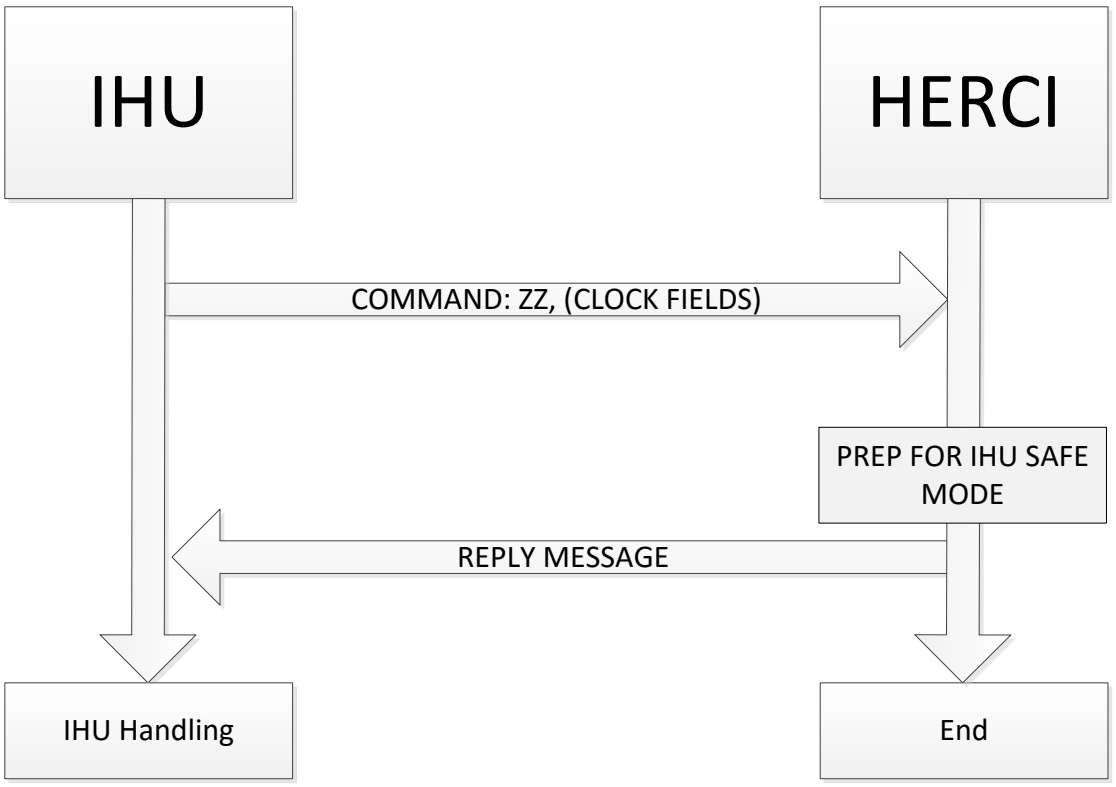
6.3 RR COMMAND

HERCI responds to the RR command by returning the last telemetry transport frame sent to IHU embeddedin the response. The RR command will only occur immediately following a PP command.



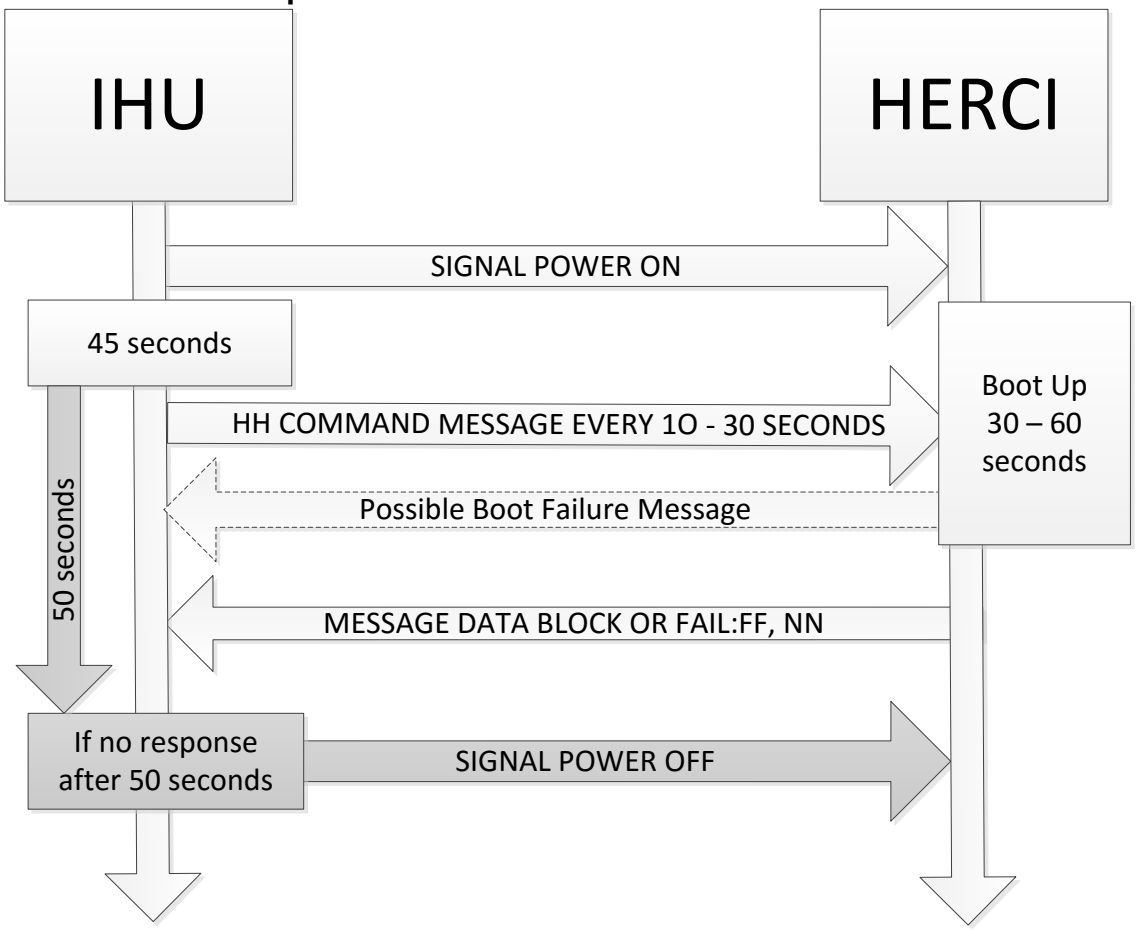
6.4 ZZ COMMAND

HERCI responds to the ZZ command by stopping data collection and closing its data file system.The ZZ command may occur at any time.



7 Power On Diagram

7.1 Power On Sequence



Date: March 2, 2015
Version: Version 2.11

AMSAT *Fox-1*

IHU to MPPT PSU Interface Control Document

1 Introduction

This document specifies the message interface between the Internal Housekeeping Unit (IHU) and the MPPT Power Supply (PSU) System, as required per the AMSAT *Fox-1* System Requirements Specification document.

1.1 Document History

DATE	VERSION	SUMMARY
February 21, 2012	1.0	Initial version
February 21, 2012	1.01	Clarify I²C address
March 7, 2012	1.02	2.3.1 updated Vdd to 3.0V
August 7, 2012	1.03	Remove BATT1 data fields and adjust message accordingly
November 7, 2012	1.04	Added PSU CPU Temperature
December 27, 2012	1.10	Change from Bytes to Bits in Message Header Block, Message Data Block, Message Data (to allow for 12 bit ADC values)
January 2, 2013	1.11	Field sizes back to bytes account I²C specifications
February 7, 2013	1.12	Correct typo in 3.3.1.1
August 22, 2013	1.13	Remove TOTAL I from Data block
August 22, 2013	1.14	Update I²C speed to 10 kHz
October 4, 2013	2.00	Rework to eliminate STM32L and replace with ADS7828s
November 18, 2013	2.01	Change telemetry sample rate in 2.2.1 to 4 seconds
June 10, 2014	2.1	Update Table 1 and Table 2 to reflect actual construction, add PSU Output Current to Table 1, swap addresses for Device 1 and Device 2 to account for construction error
March 2, 2015	2.11	Updated ADC Channel tables

1.2 Document Scope

The purpose of this document is to specify the message format and the I²C bus hardware operation for the communications between the IHU and the MPPT PSU as described in the AMSAT *Fox-1* System Requirements Specification.

1.3 References

1. AMSAT *Fox-1*, System Requirements Specification
2. AMSAT *Fox-1*, System Design Specification
3. AMSAT *Fox-1*, IHU Software Architecture Specification

2 General Messaging Requirements

2.1 Link Protocol Requirements

2.1.1 The IHU shall be the I²C Master.

2.1.2 The MPPT PSU shall be the I²C Slave.

2.1.2.1 The IHU shall request the MPPT PSU to send the data for a specific Device and channel.

2.1.2.2 The MPPT PSU shall send that specific Device and channel data.

2.1.3 The IHU shall test for the presence both MPPT PSU system Devices.

2.1.4 The IHU shall only poll the MPPT PSU system Device(s) present, for data.

2.2 General Message Requirements

2.2.1 The IHU shall sample data at a rate sufficient to provide downlink telemetry data every 4 seconds.

2.2.2 For both Devices the ADS 7820 A/D converter shall always be commanded on (PD-0 bit = 1).

2.2.3 For both Devices the ADS 7820 Internal Reference shall always be commanded on (PD-1 bit = 1).

2.2.4 TFor both Devices the ADS 7820 shall always be commanded for single-ended inputs.

2.3 I²C Bus Hardware Interface Requirements

2.3.1 The I²C Vdd shall be 3.0V.

2.3.2 The bus speed shall be Standard (10 kHz).

2.3.3 The MPPT PSU system Device 1 I²C 7 bit address shall be 0x4A.

2.3.4 The MPPT PSU system Device 2 I²C 7 bit address shall be 0x49.

3 Message Content Requirements

3.1 Measured Values

3.1.1 The measured data fields for Device 1 and their associated ADS 7828 channels shall be as shown in Table 1.

Table 1

Field	Channel	Type	Min Value	Max Value	Description
+X PANEL V	0	Unsigned	0x00	0xFFF	+X PANEL V
-X PANEL V	1	Unsigned	0x00	0xFFF	-X PANEL V
+Y PANEL V	2	Unsigned	0x00	0xFFF	+Y PANEL V
-Y PANEL V	3	Unsigned	0x00	0xFFF	-Y PANEL V
+Z PANEL V	4	Unsigned	0x00	0xFFF	+Z PANEL V
-Z PANEL V	5	Unsigned	0x00	0xFFF	-Z PANEL V
MPPT VOUT	6	Unsigned	0x00	0xFFF	MPPT VBATT V
Not used	7	-	-	-	-

3.1.2 The measured data fields for Device 2 and their associated ADS 7828 channels shall be as shown in Table 2.

Table 2

Field	Channel	Type	Min Value	Max Value	Description
MPPT PCB Temperature	0	Unsigned	0x00	0xFFF	Temperature of MPPT card
-Y PANEL T	1	Unsigned	0x00	0xFFF	-Y PANEL T
+Z PANEL T	2	Unsigned	0x00	0xFFF	+Z PANEL T
+X PANEL T	3	Unsigned	0x00	0xFFF	+X PANEL T
MPPT Current	4	Unsigned	0x00	0xFFF	MPPT Output Current
+Y PANEL T	5	Unsigned	0x00	0xFFF	+Y PANEL T
-X PANEL T	6	Unsigned	0x00	0xFFF	-X PANEL T
-Z PANEL T	7	Unsigned	0x00	0xFFF	-Z PANEL T

3.1.3 Measurements shall be made in relation to the 2.5 VDC internal voltage reference for both ADS 7828 Devices.

3.1.4 For each Device the IHU shall poll each channel in channel number order.

Date: June 9, 2015
Version: Version 1.10

AMSAT *Fox-1C/D*

IHU to "L-Band DOWNSHIFTER" Interface Control Document

1 Introduction

This document specifies the message interface between the Internal Housekeeping Unit (IHU) and the payload in Experiment Position 4 of the satellite, known as the L-Band DOWNSHIFTER and abbreviated herein as EXP4.

1.1 Document History

DATE	VERSION	SUMMARY
June 7, 2015	1.00	Initial version
June 9, 2015	1.10	Added 2.1.2

1.2 Document Scope

This document will specify the control of EXP4, and the IHU operation of EXP4.

1.3 References

1. AMSAT *Fox-1*, System Requirements Specification
2. AMSAT *Fox-1*, System Design Specification
3. AMSAT *Fox-1*, IHU Software Architecture Specification

2 EXP4 Operation

2.1 EXP4 Power Control

2.1.1 The IHU shall exert control over the power state of the EXP4 by the Experiment Enable 3 pin on the satellite bus as shown in Table 1.

Table 1

Pin State	Voltage	Description
High	≥ 2.4	Power On Experiment
Low, or high-impedance	< 2.4	Power Off Experiment

2.1.2 EXP4 may draw current from the system bus while in the OFF state in order to power the antenna path switching circuits required for its operation.

2.2 EXP4 Power On Sequence

2.2.1 Upon receiving an L-BAND MODE command the IHU shall set and hold the Experiment Enable 3 pin HIGH.

2.3 EXP4 Operation

2.3.1 Upon receiving an L-BAND MODE command the IHU shall perform the following actions.

2.3.1.1 Operating mode shall be set to TRANSPONDER MODE.

2.3.1.2 A software timer shall be started to count down 86400 seconds.

2.3.1.2.1 At the expiration of the timer, the IHU shall perform the EXP4 Power Off Sequence.

2.3.2 Upon receiving an L-BAND MODE command while the software timer is running, the software timer shall begin counting down from 86400 seconds.

2.3.3 Upon receiving any command other than an L-BAND MODE command the IHU shall perform the EXP4 Power Off Sequence.

2.3.4 The default power state for EXP4 on IHU restart shall be OFF.

2.4 EXP4 Power Off Sequence

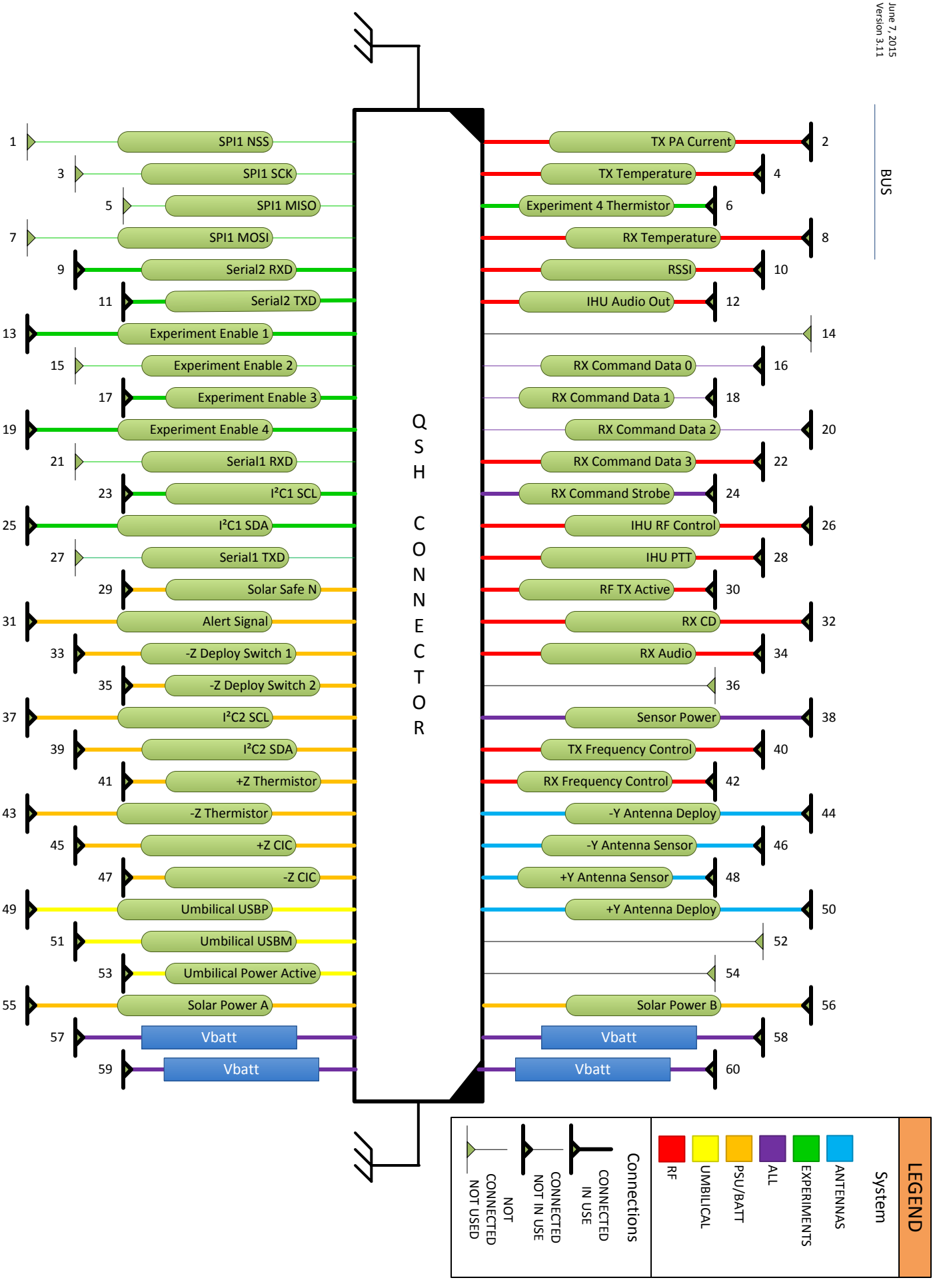
2.4.1 The IHU shall set the Experiment Enable 3 pin LOW.

2.4.1.1 The absence of a HIGH state on the Experiment Enable 3 pin shall be construed as a LOW state whether the pin is actually LOW, or in a high-impedance state.

2.4.2 The software timer shall be stopped.

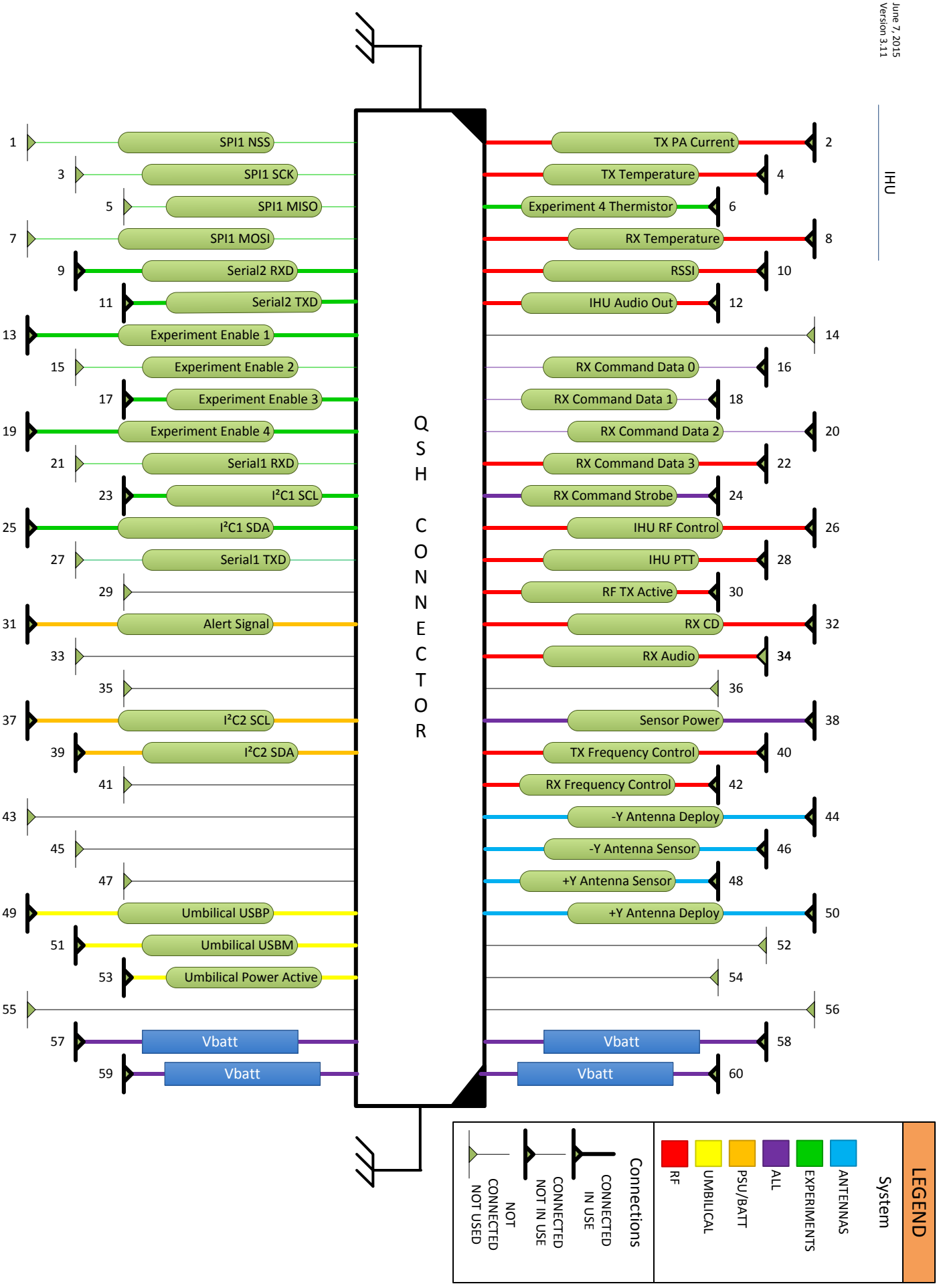
June 7, 2015
Version 3.11

BUS



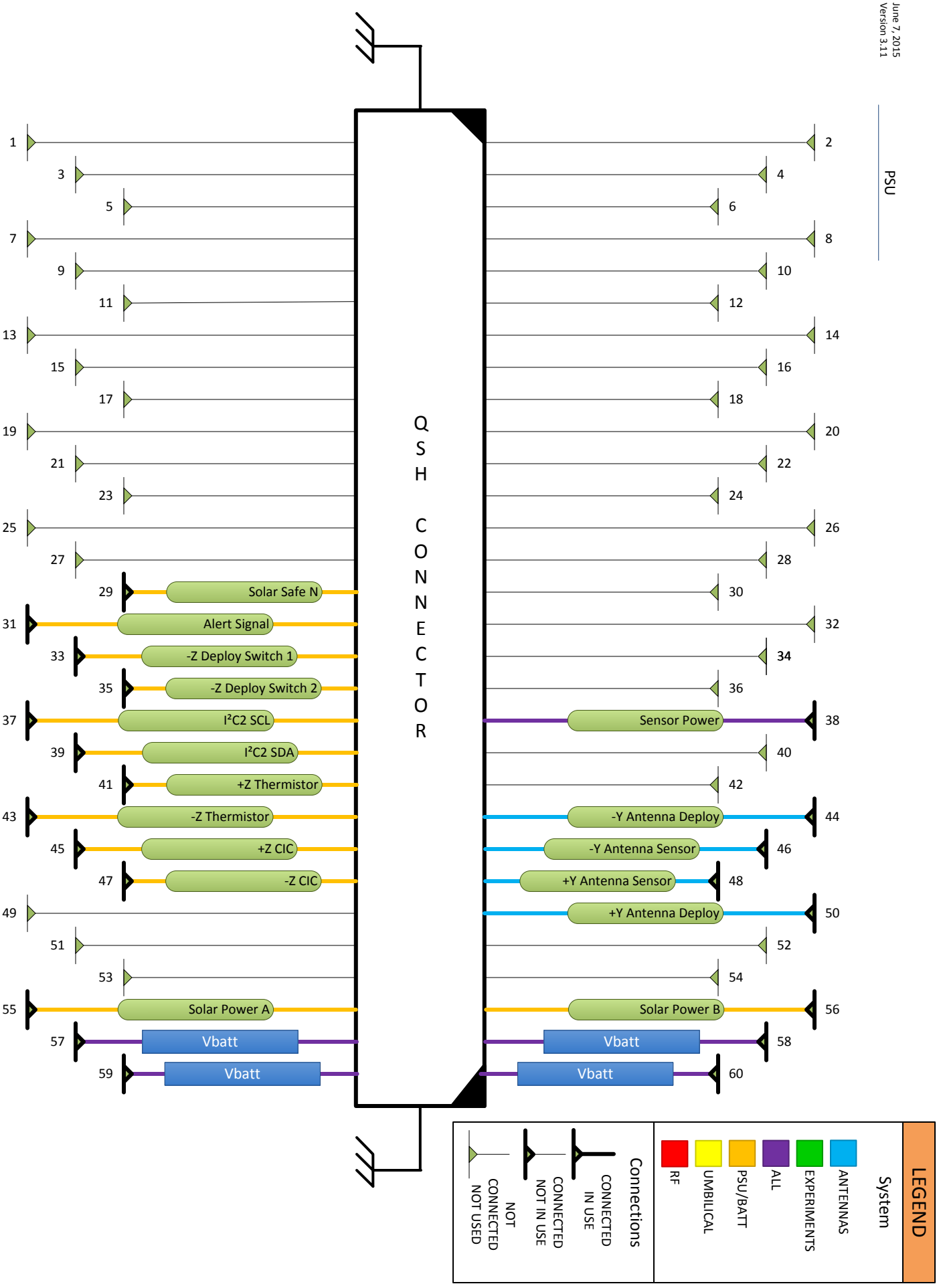
June 7, 2015
Version 3.11

IHU



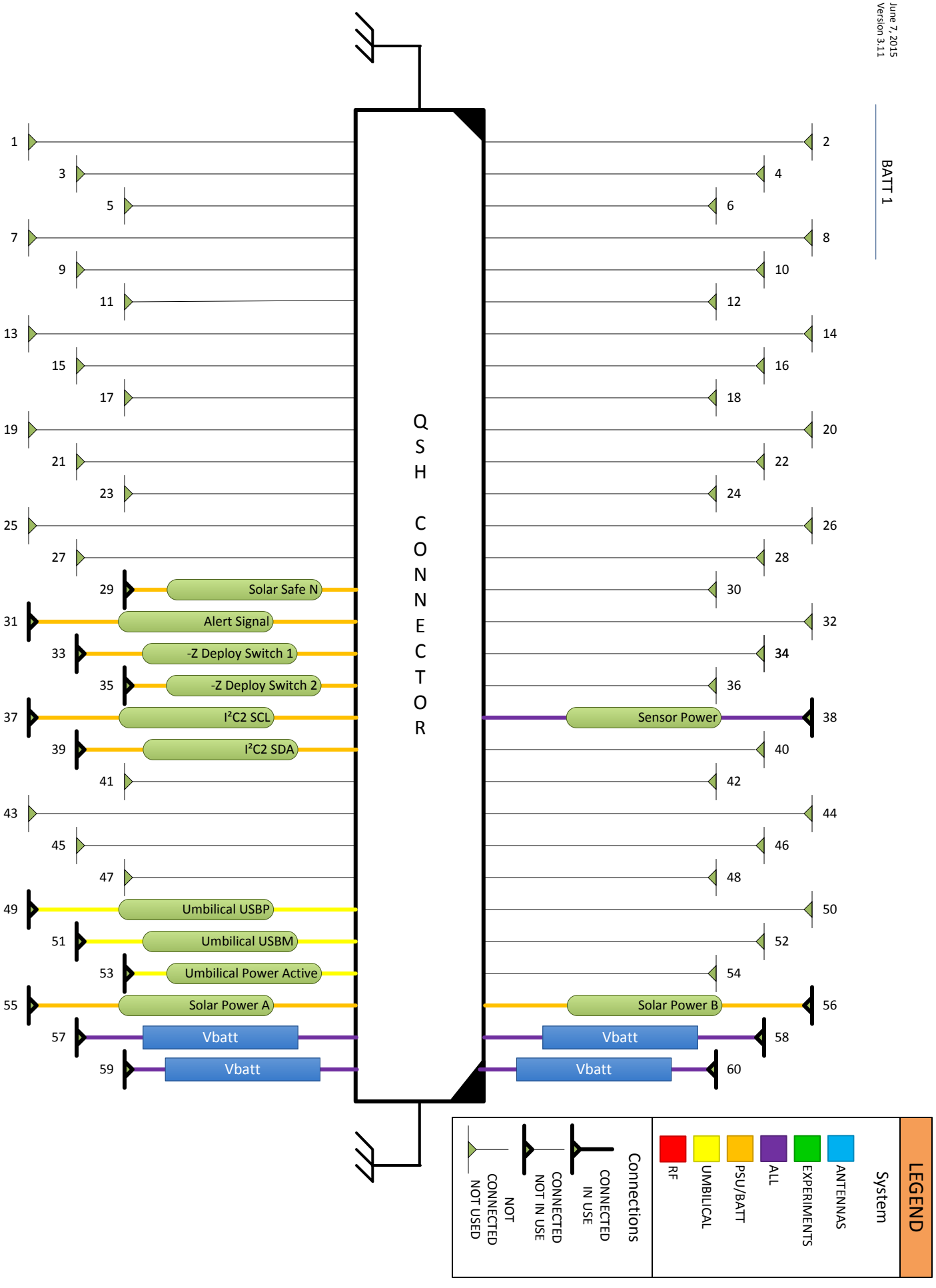
June 7, 2015
Version 3.11

PSU



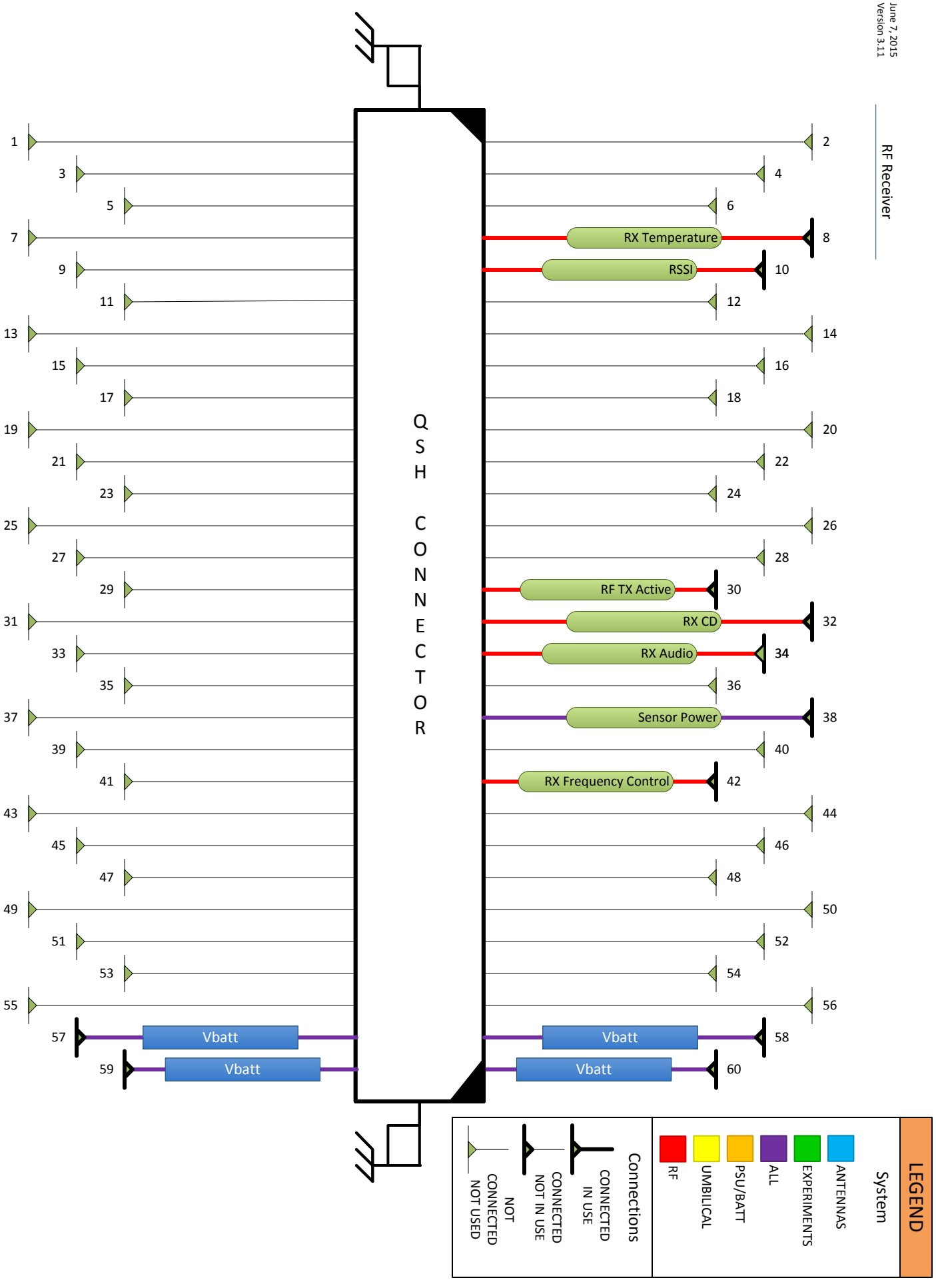
June 7, 2015
Version 3.11

BATT 1



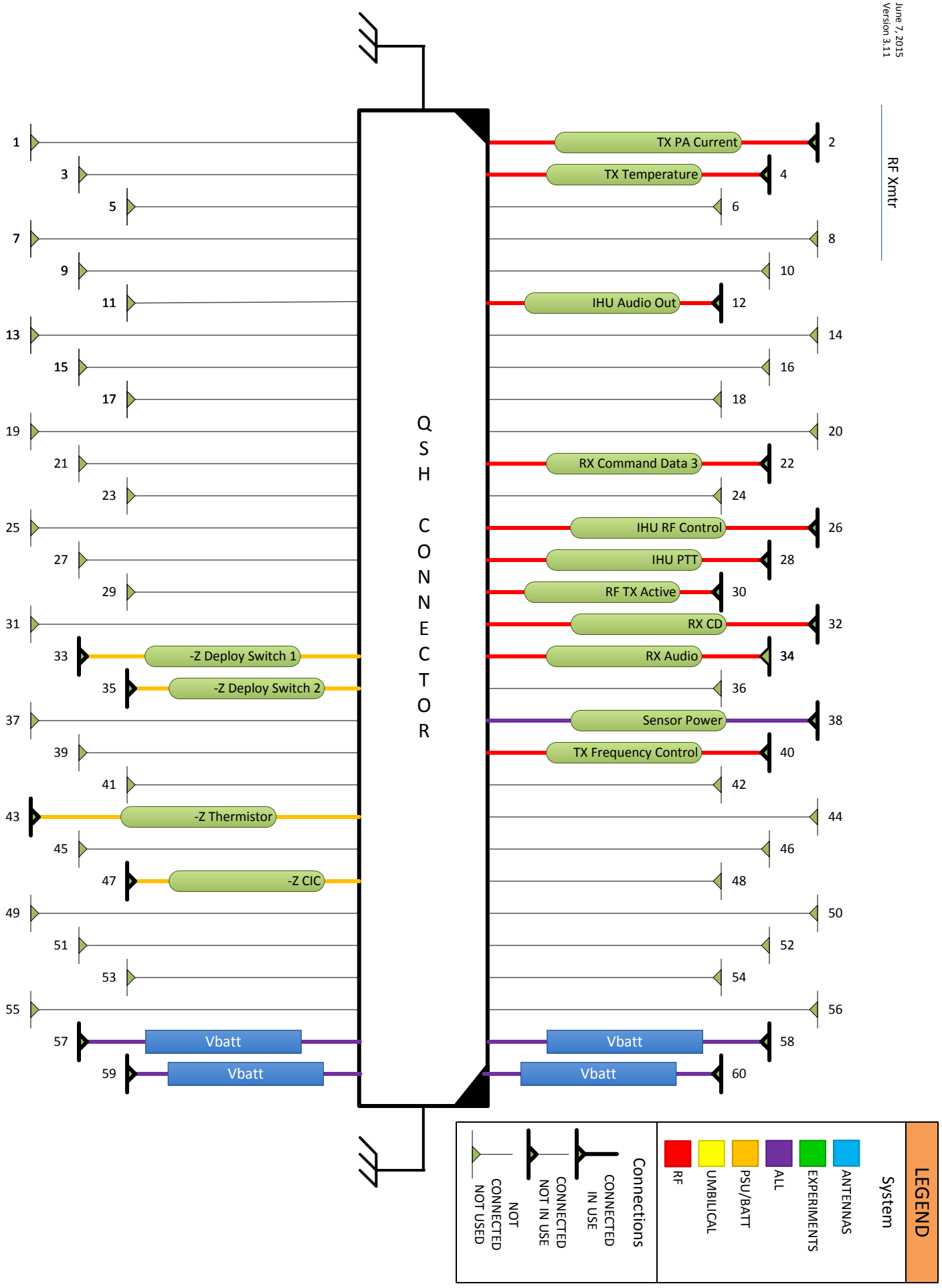
June 7, 2015
Version 3.11

RF Receiver



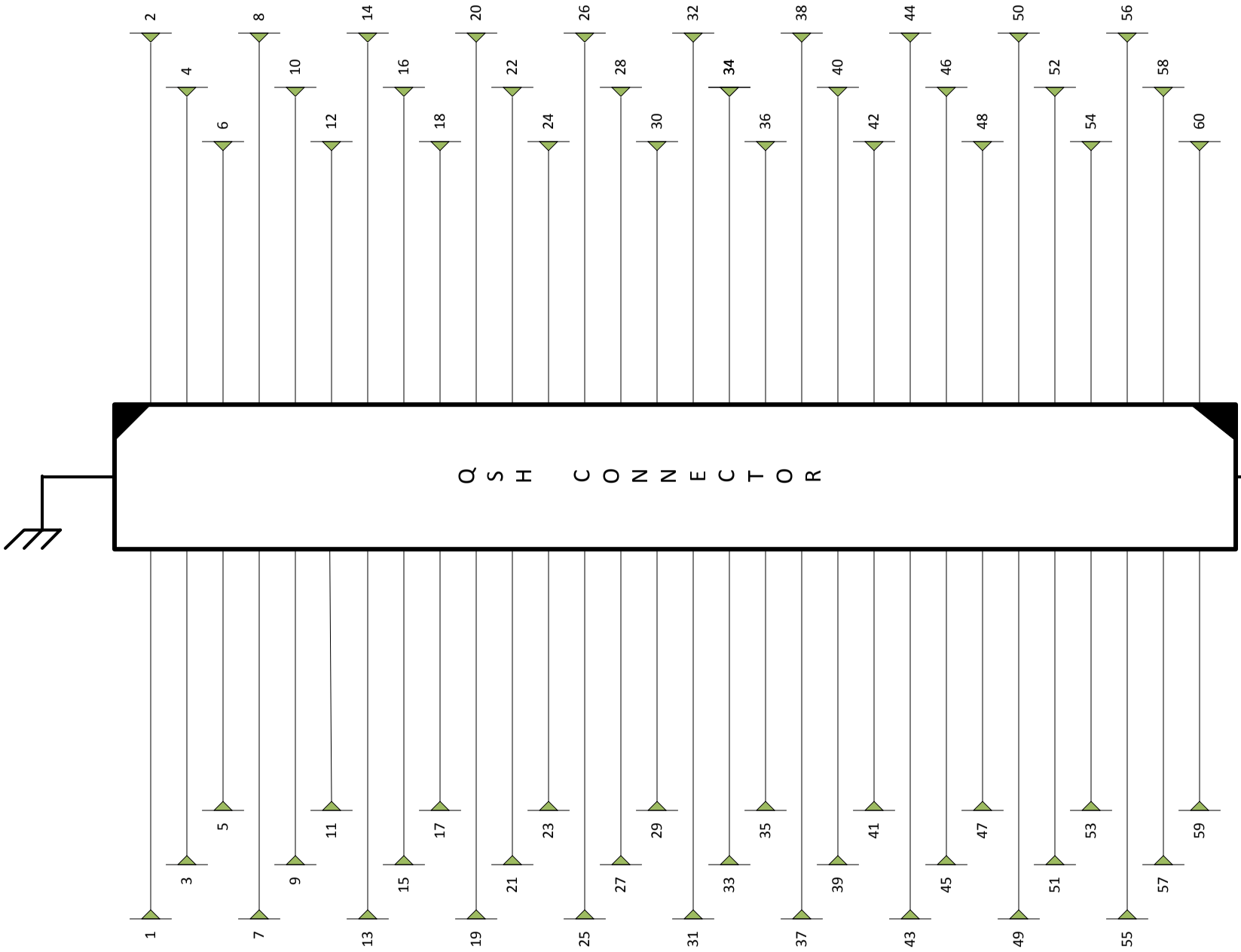
June 7, 2015
Version 3.11

RF Xmtr



June 7, 2015
Version 3.11

BATT 2



LEGEND

System

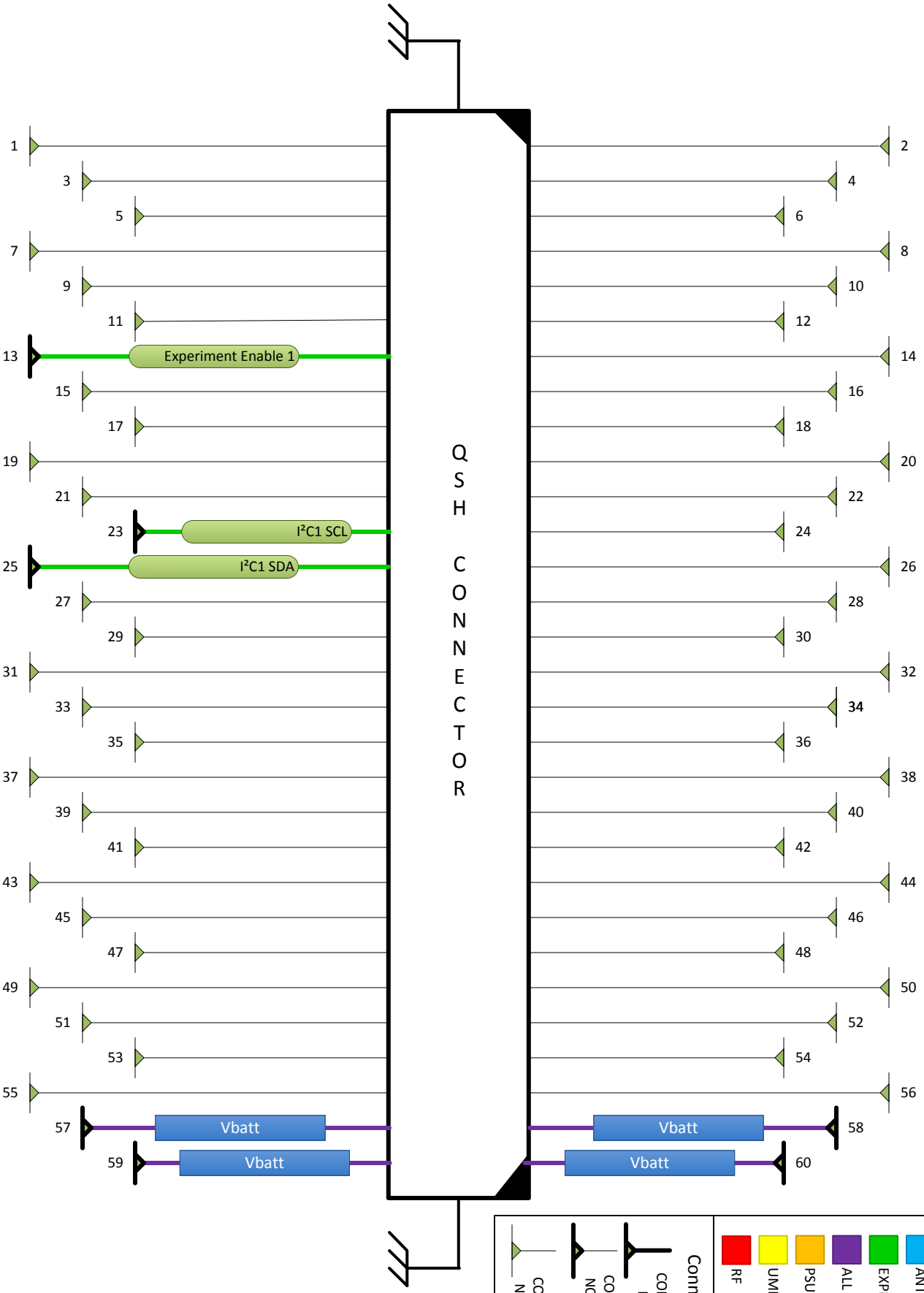
- ANTENNAS
- EXPERIMENTS
- ALL
- PSU/BATT
- UMBILICAL
- RF

Connections

- CONNECTED IN USE
- CONNECTED NOT IN USE
- NOT CONNECTED NOT USED

June 7, 2015
Version 3.11

VUC



LEGEND

System

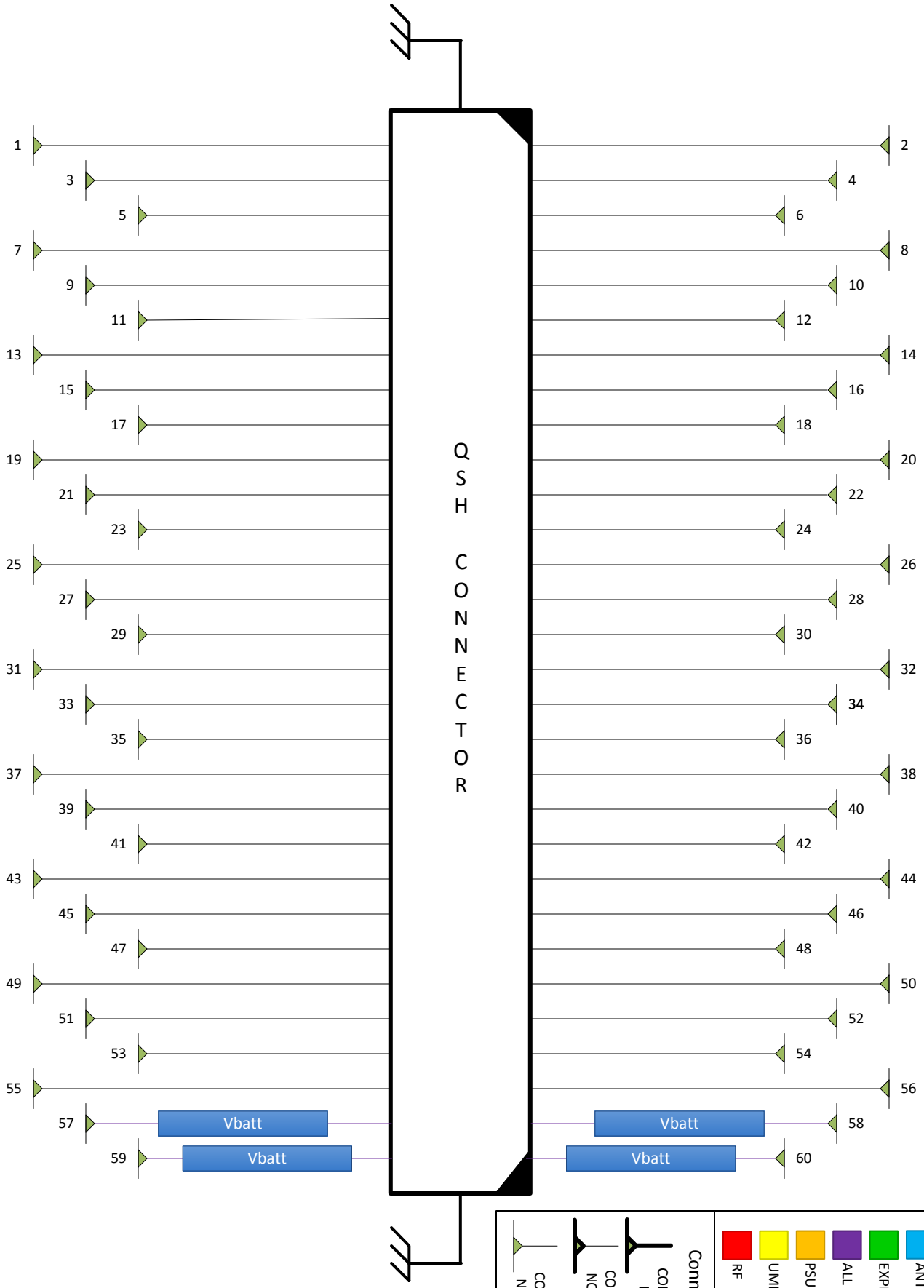
- ANTENNAS
- EXPERIMENTS
- ALL
- PSU/BATT
- UMBILICAL
- RF

Connections

- CONNECTED IN USE
- CONNECTED NOT IN USE
- NOT CONNECTED NOT USED

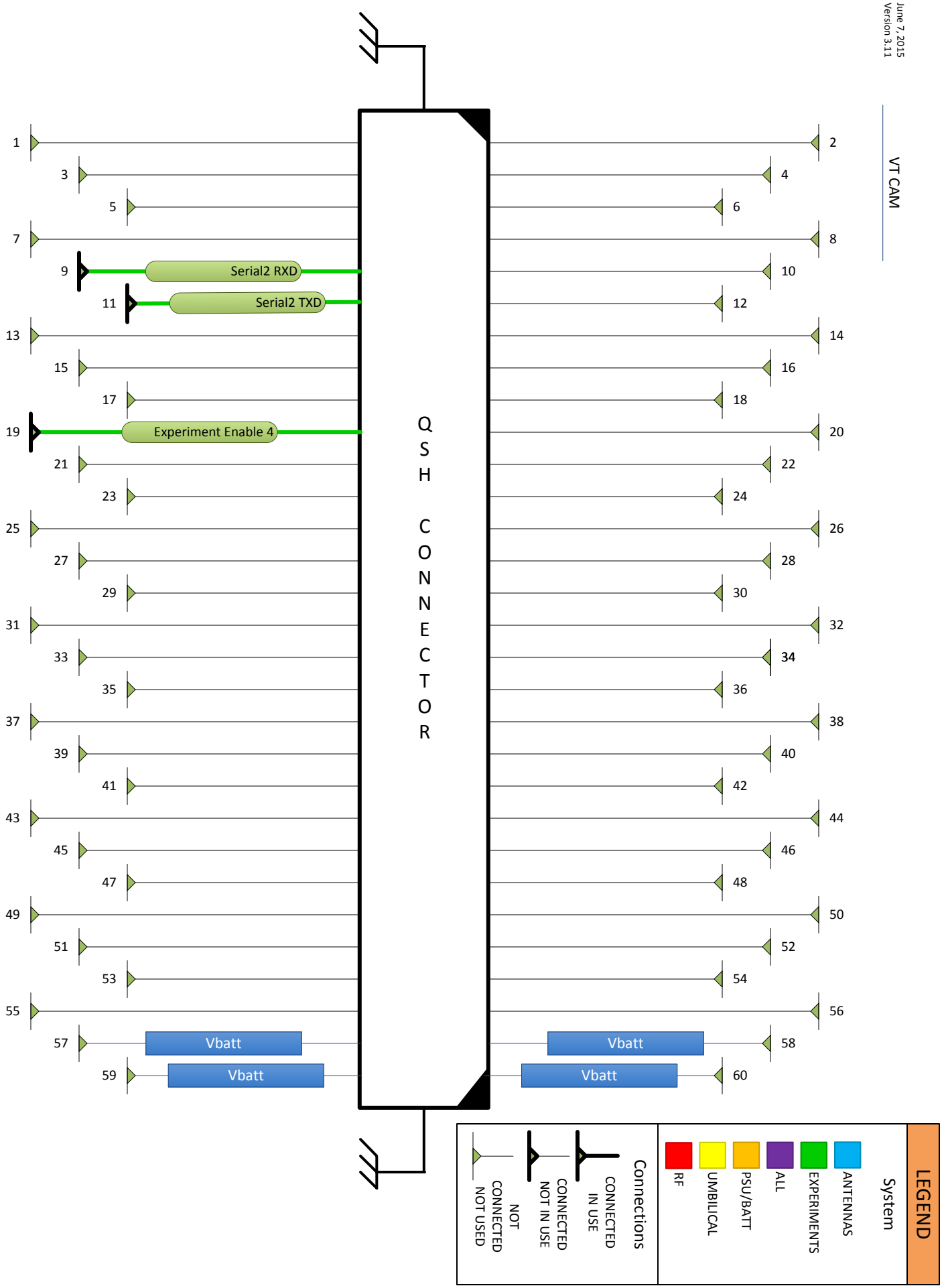
June 7, 2015
Version 3.11

EXP 2



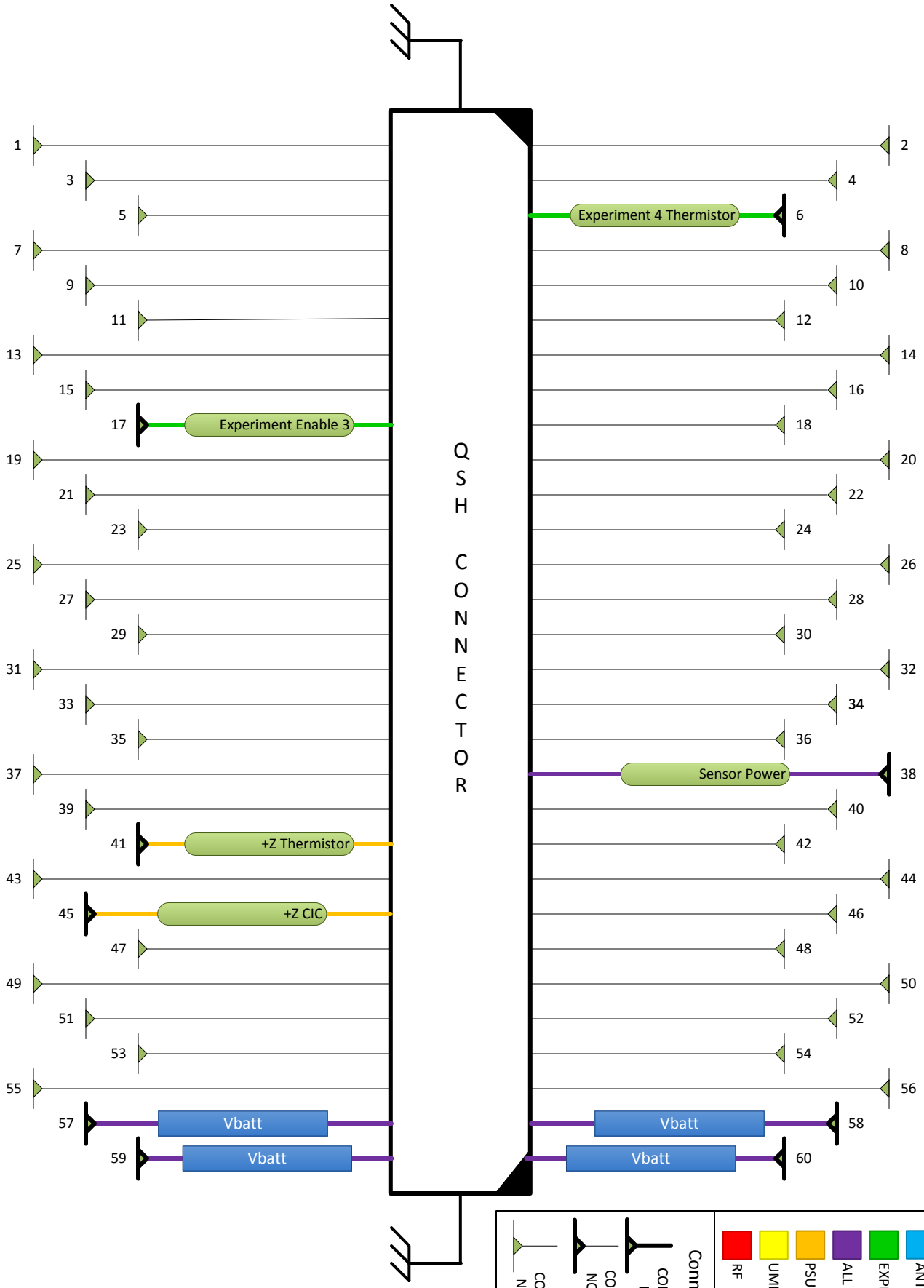
June 7, 2015
Version 3.11

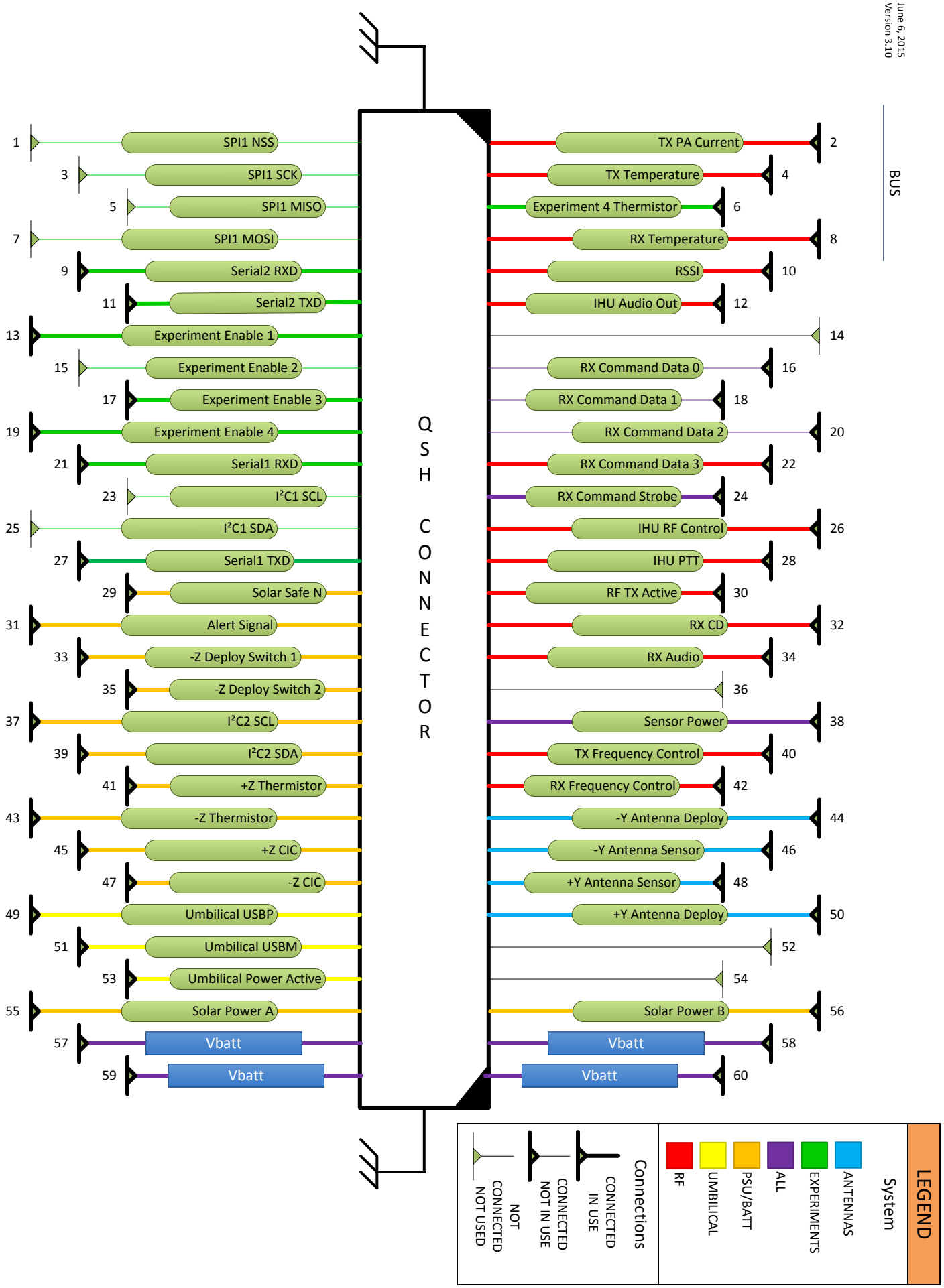
VT CAM



June 7, 2015
Version 3.11

L BAND




June 6, 2015
Version 3.10
BUS
QSH CONNECTOR
1 SPI1 NSS
3 SPI1 SCK
5 SPI1 MISO
7 SPI1 MOSI
9 Serial2 RXD
11 Serial2 TXD
13 Experiment Enable 1
15 Experiment Enable 2
17 Experiment Enable 3
19 Experiment Enable 4
21 Serial1 RXD
23 I²C1 SCL
25 I²C1 SDA
27 Serial1 TXD
29 Solar Safe N
31 Alert Signal
33 -Z Deploy Switch 1
35 -Z Deploy Switch 2
37 I²C2 SCL
39 I²C2 SDA
41 +Z Thermistor
43 -Z Thermistor
45 +Z CIC
47 -Z CIC
49 Umbilical USBP
51 Umbilical USBM
53 Umbilical Power Active
55 Solar Power A
57 Vbatt
59 Vbatt
2 TX PA Current
4 TX Temperature
6 Experiment 4 Thermistor
8 RX Temperature
10 RSSI
12 IHU Audio Out
14
16 RX Command Data 0
18 RX Command Data 1
20 RX Command Data 2
22 RX Command Data 3
24 RX Command Strobe
26 IHU RF Control
28 IHU PTT
30 RF TX Active
32 RX CD
34 RX Audio
36
38 Sensor Power
40 TX Frequency Control
42 RX Frequency Control
44 -Y Antenna Deploy
46 -Y Antenna Sensor
48 +Y Antenna Sensor
50 +Y Antenna Deploy
52
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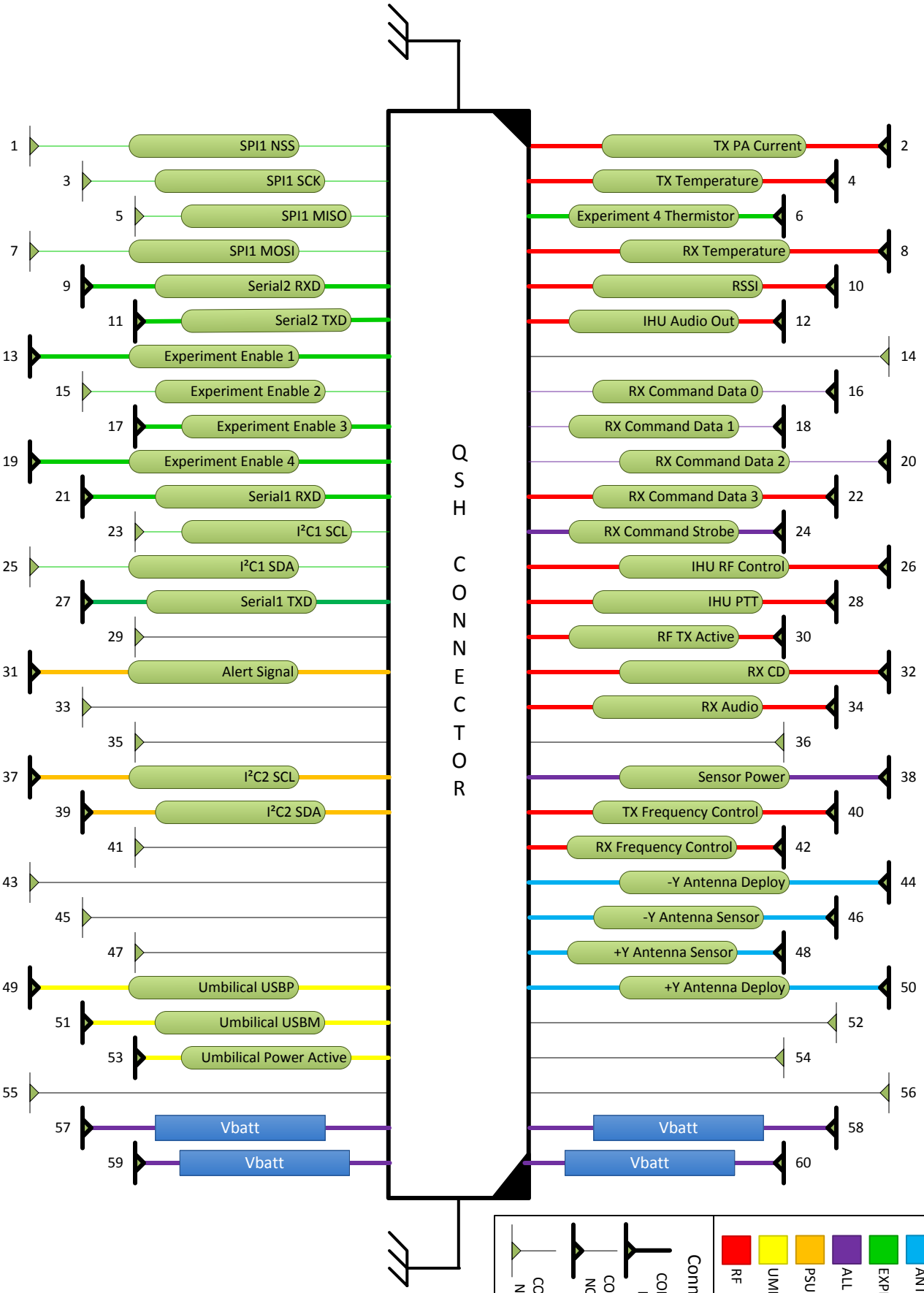
56 Solar Power B
58 Vbatt
60 Vbatt
LEGEND
System
ANTENNAS
EXPERIMENTS
ALL
PSU/BATT
UMBILICAL
RF
Connections
CONNECTED IN USE
CONNECTED NOT IN USE
NOT CONNECTED NOT USED

June 6, 2015
Version 3.10

IHU



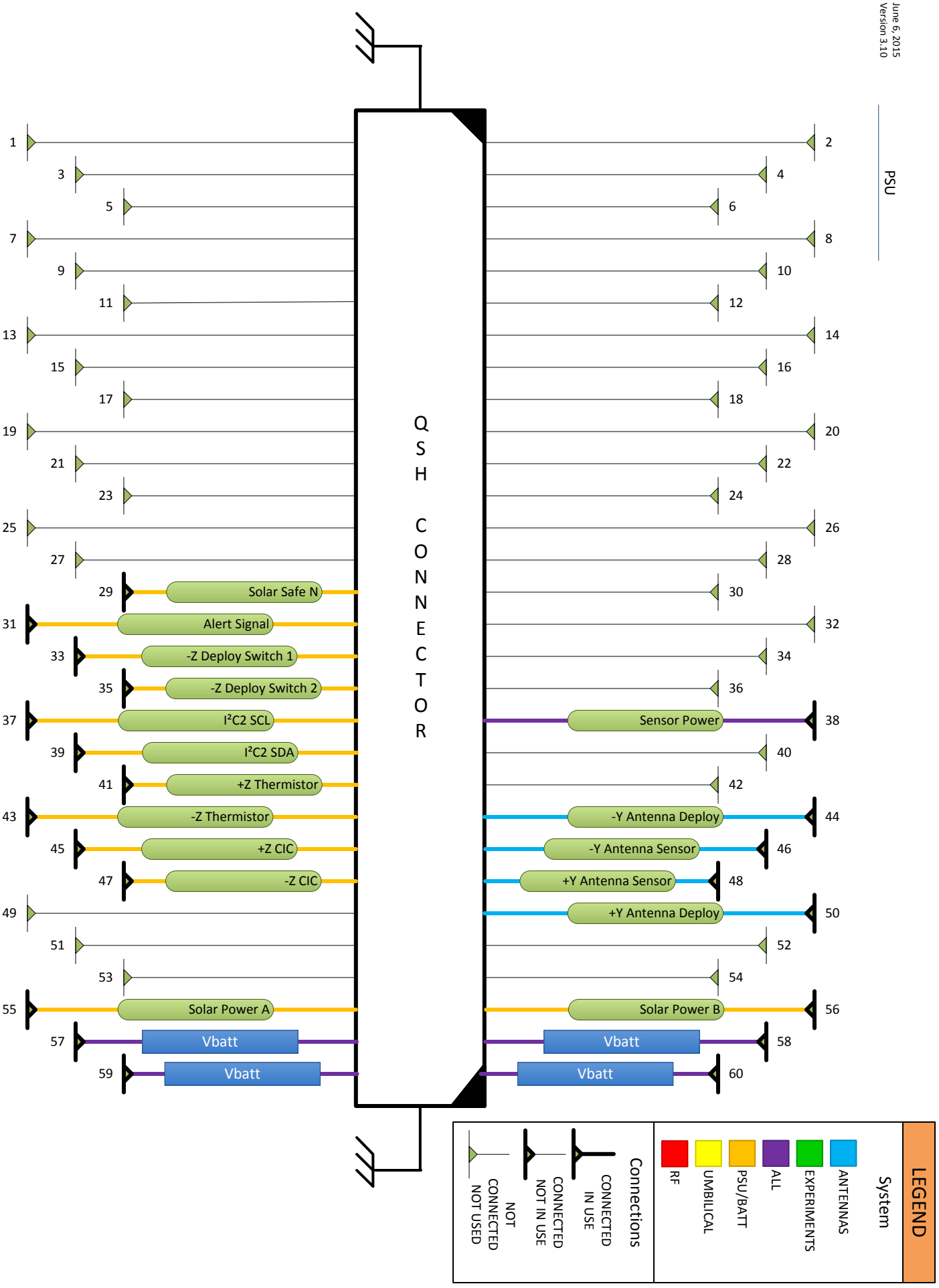
LEGEND

System: RF, UMBILICAL, PSU/BATT, ALL, EXPERIMENTS, ANTENNAS

Connections: CONNECTED IN USE, CONNECTED NOT IN USE, NOT CONNECTED NOT USED

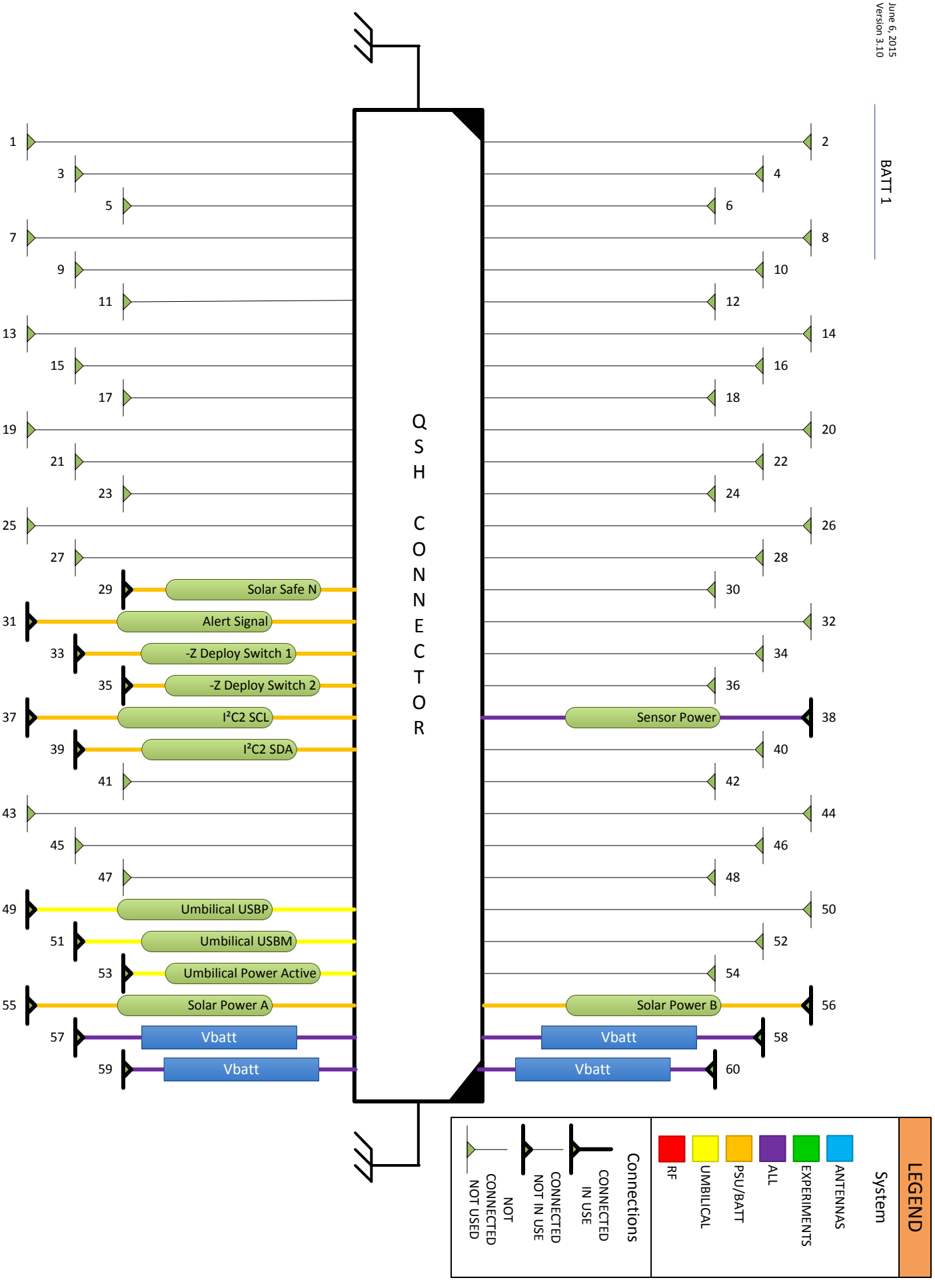
June 6, 2015
Version 3.10

PSU



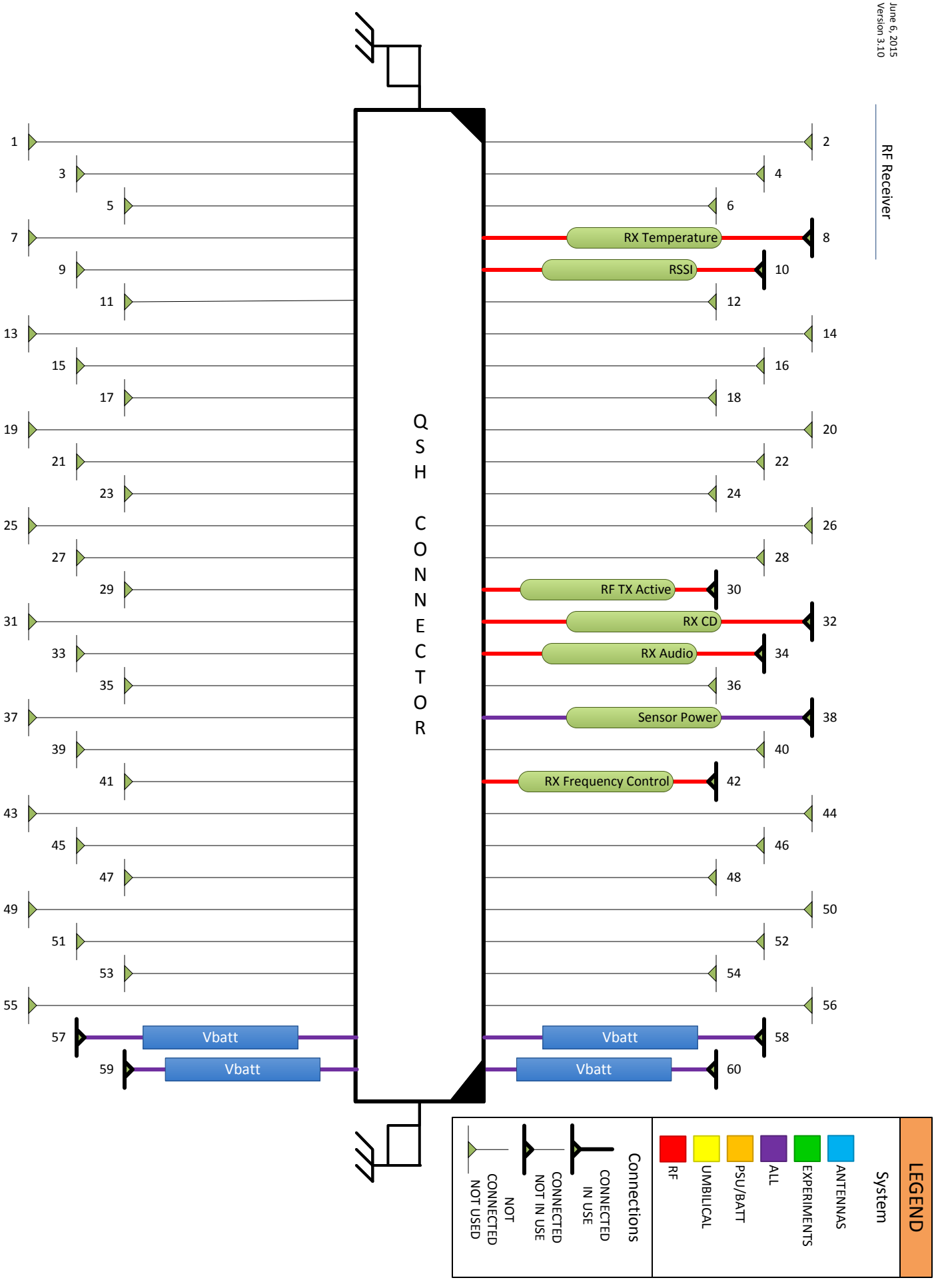
June 6, 2015
Version 3.10

BATT 1



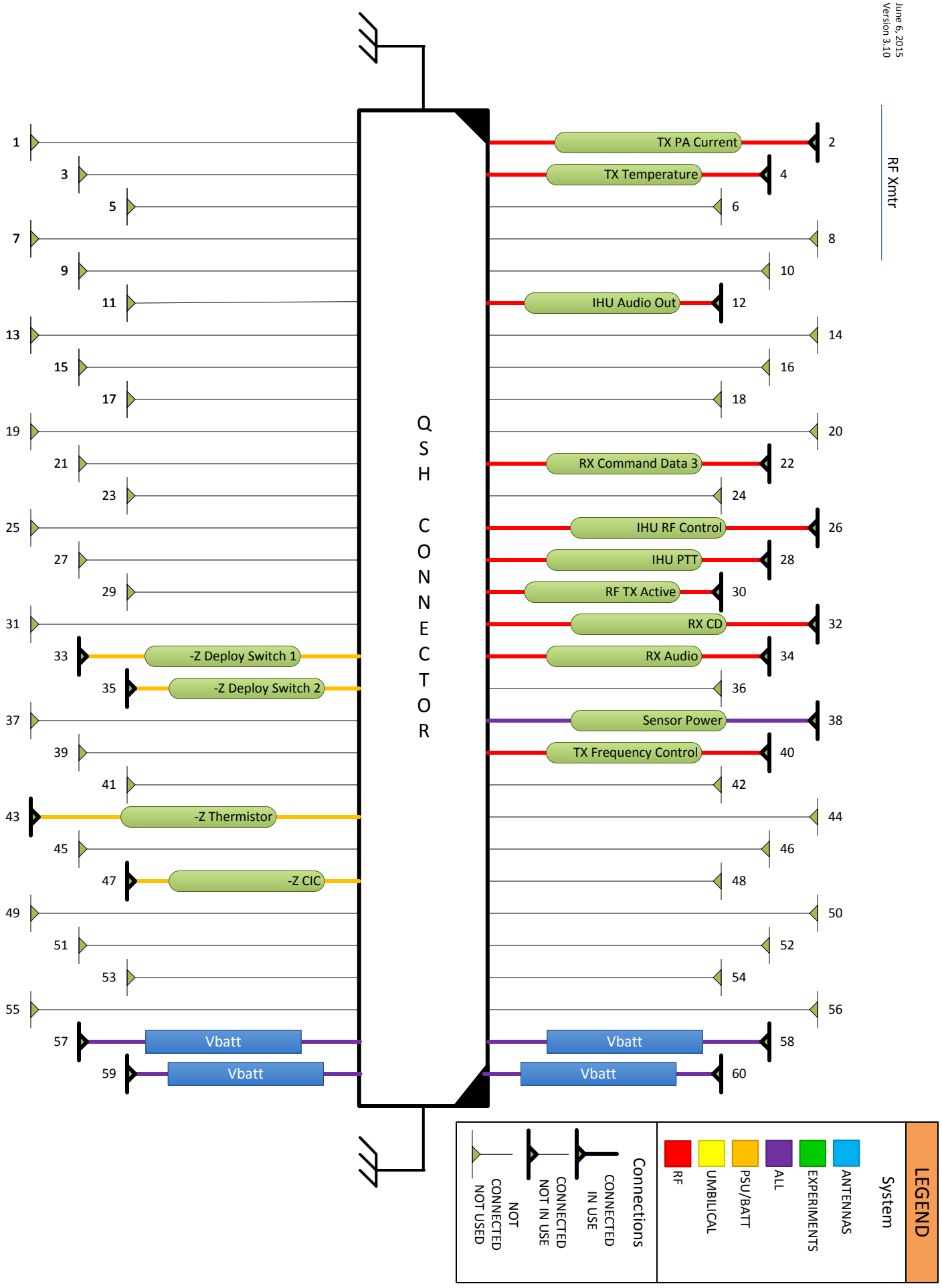
June 6, 2015
Version 3.10

RF Receiver



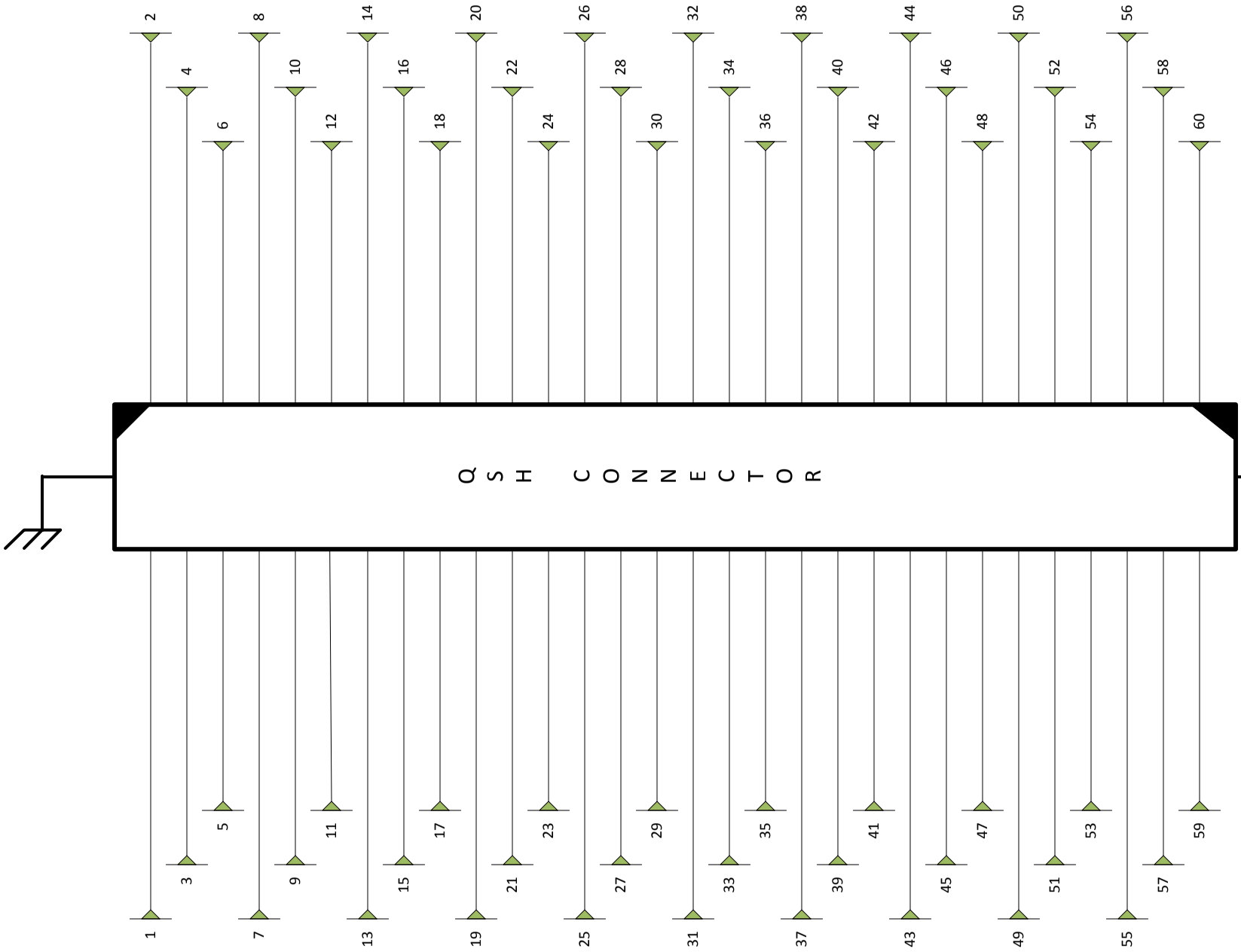
June 6, 2015
Version 3.10

RF Xmtr



June 6, 2015
Version 3.10

BATT 2



LEGEND

System

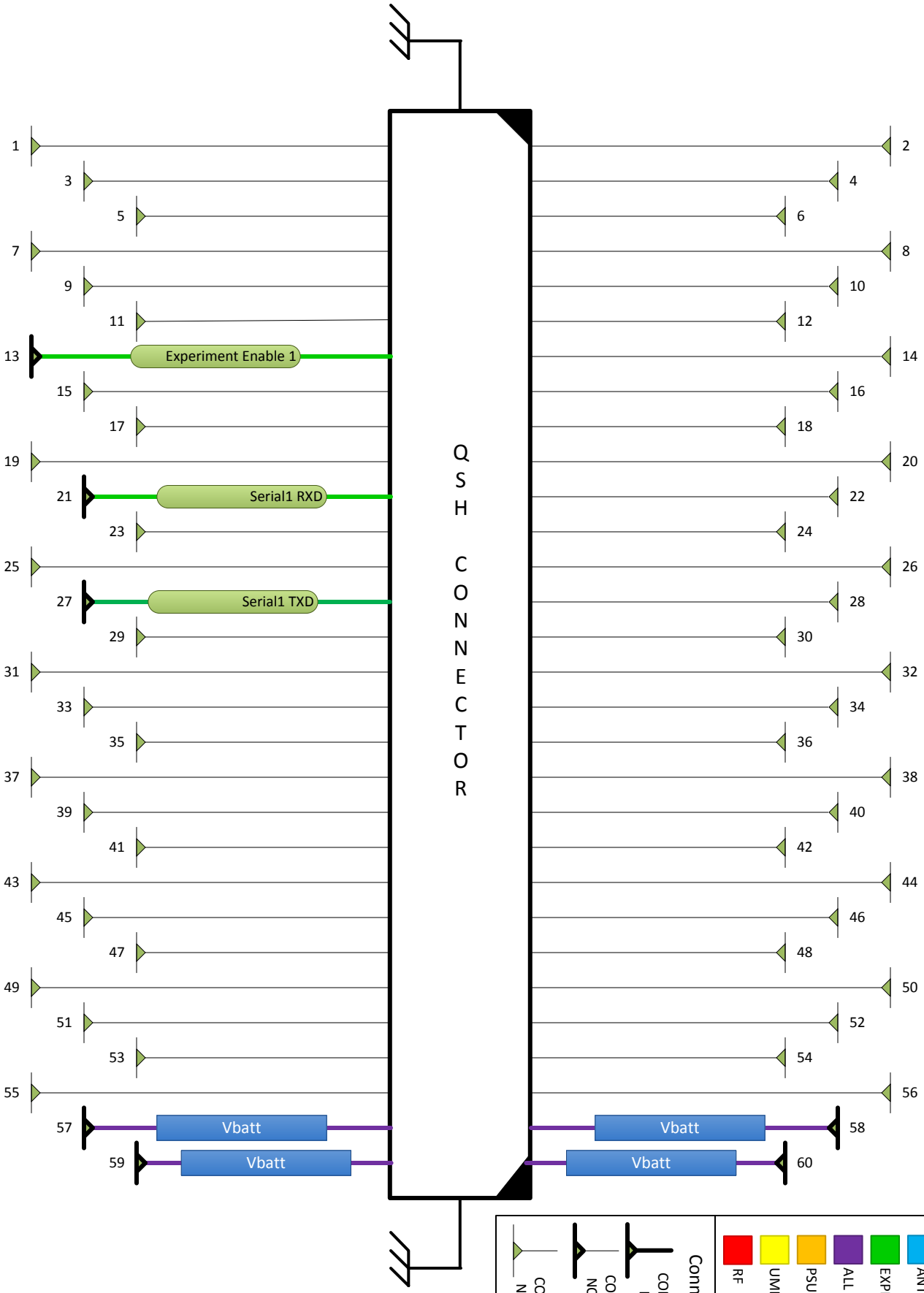
- ANTENNAS
- EXPERIMENTS
- ALL
- PSU/BATT
- UMBILICAL
- RF

Connections

- CONNECTED IN USE
- CONNECTED NOT IN USE
- NOT CONNECTED NOT USED

June 6, 2015
Version 3.10

HERCI



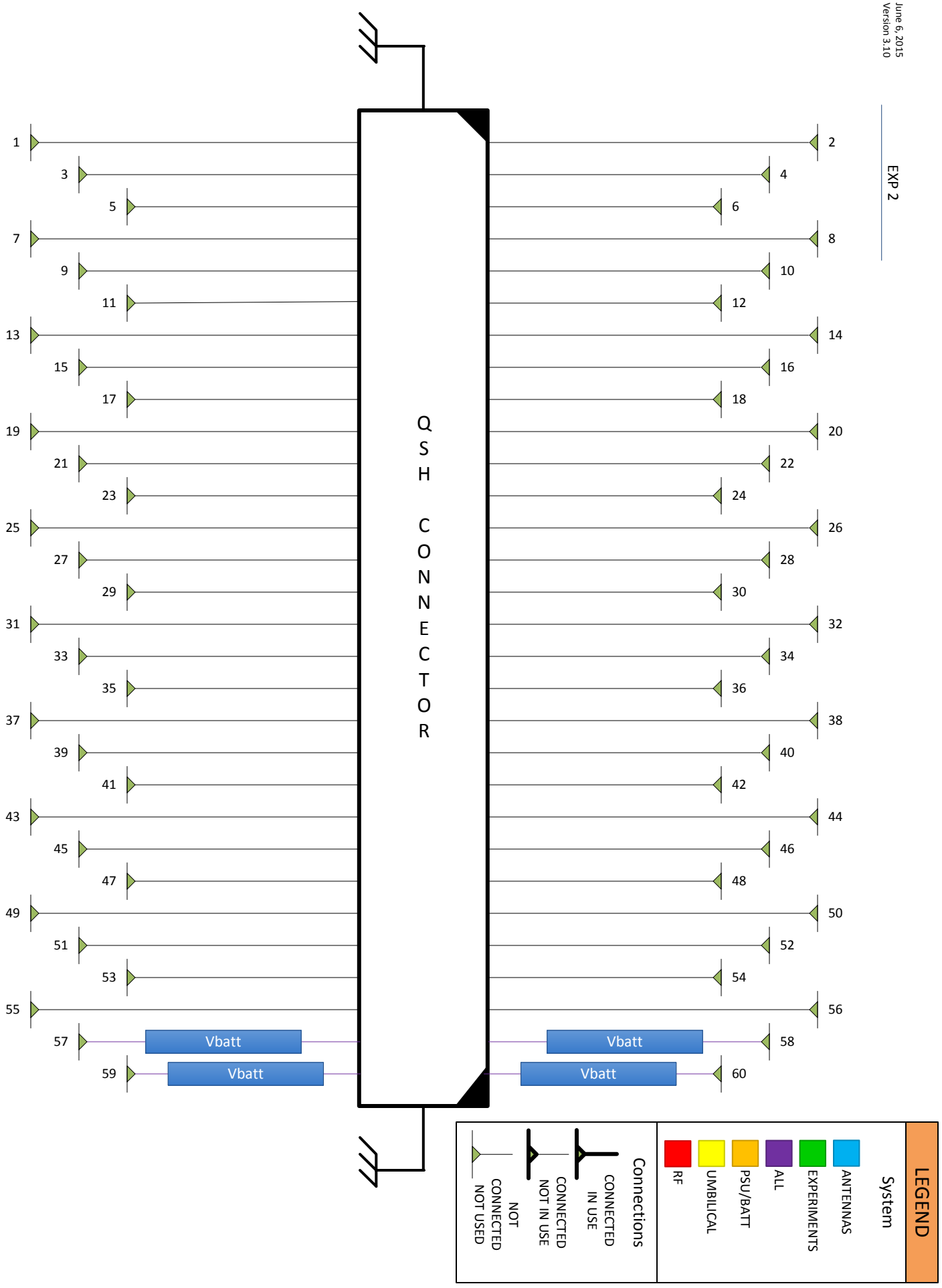
LEGEND

System

- ANTENNAS
- EXPERIMENTS
- ALL
- PSU/BATT
- UMBILICAL
- RF

Connections

- CONNECTED IN USE
- CONNECTED NOT IN USE
- NOT CONNECTED NOT USED


June 6, 2015
Version 3.10
EXP 2
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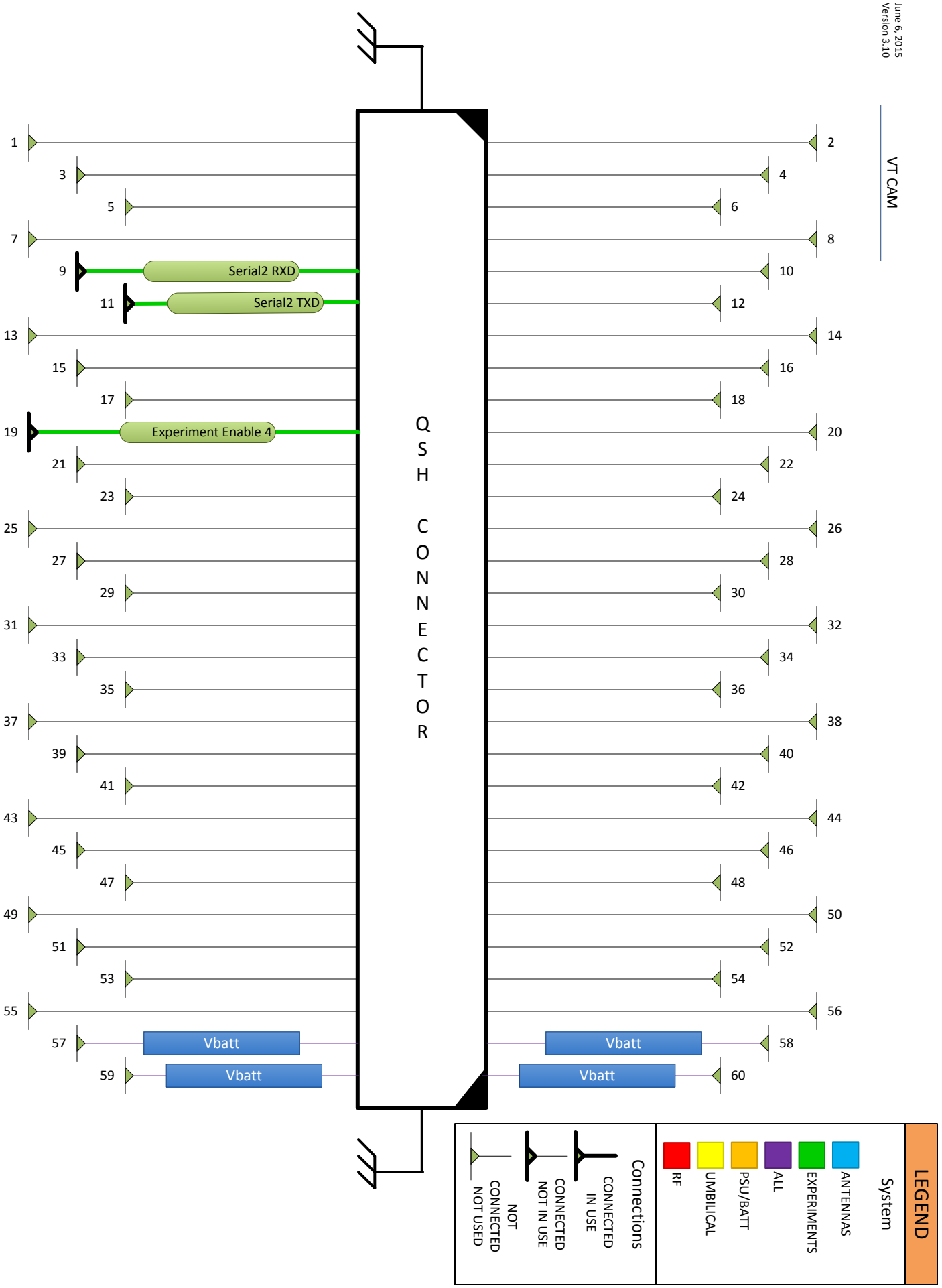
60
Vbatt
Vbatt
Vbatt
Vbatt
Q S H C O N N E C T O R
LEGEND
System
ANTENNAS
EXPERIMENTS
ALL
PSU/BATT
UMBILICAL
RF
Connections
CONNECTED IN USE
CONNECTED NOT IN USE
NOT CONNECTED NOT USED

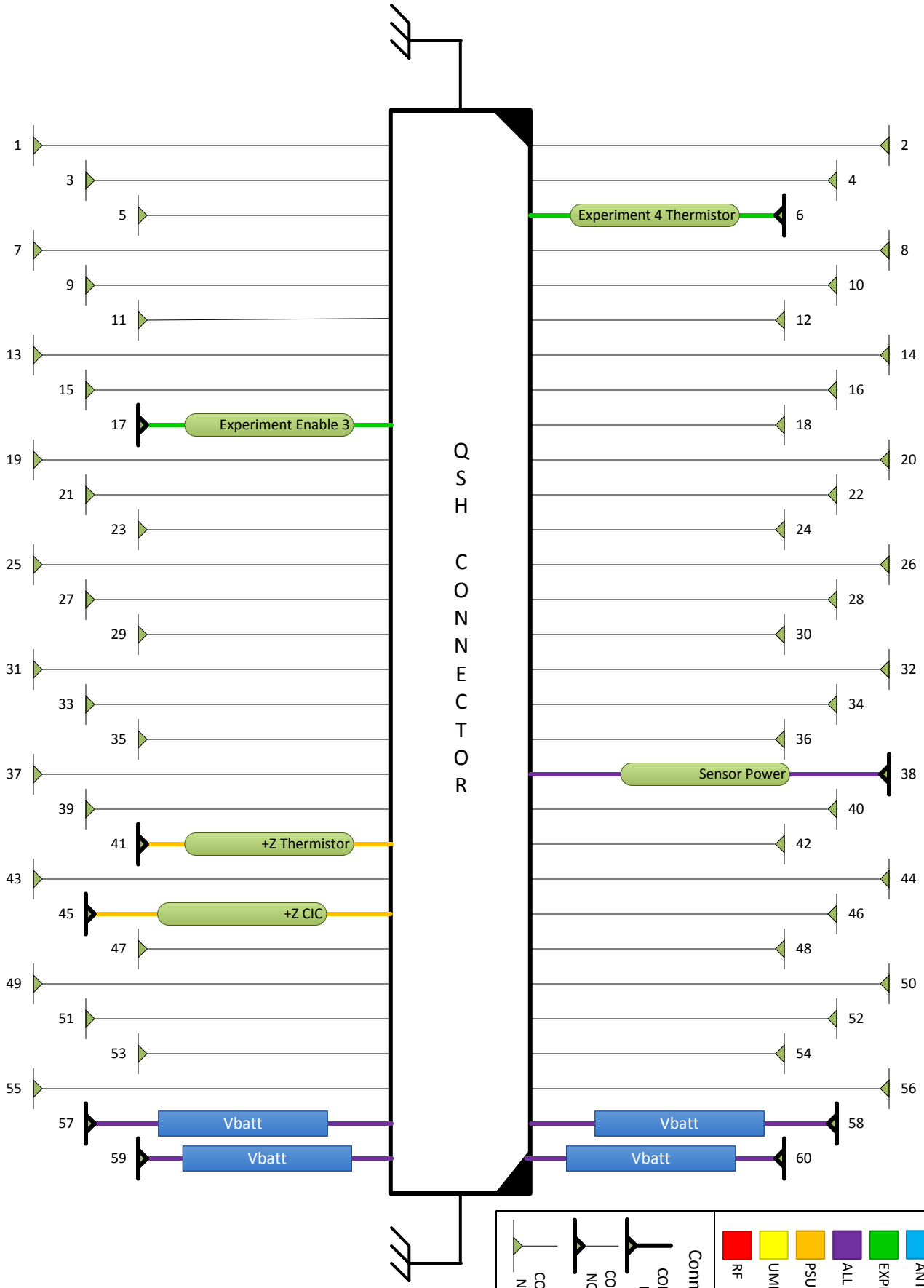
June 6, 2015
Version 3.10

VT CAM



June 6, 2015
Version 3.10

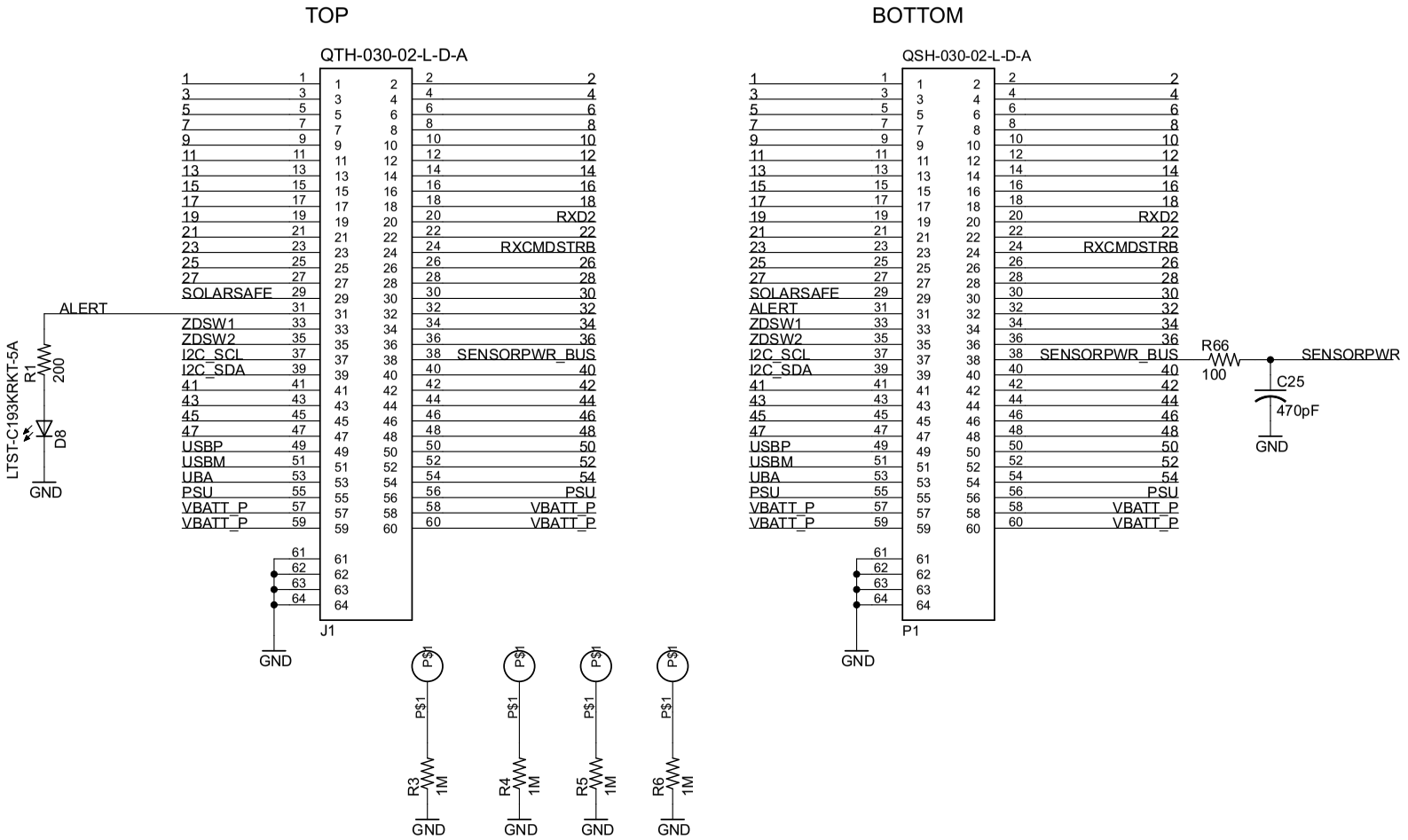
L BAND



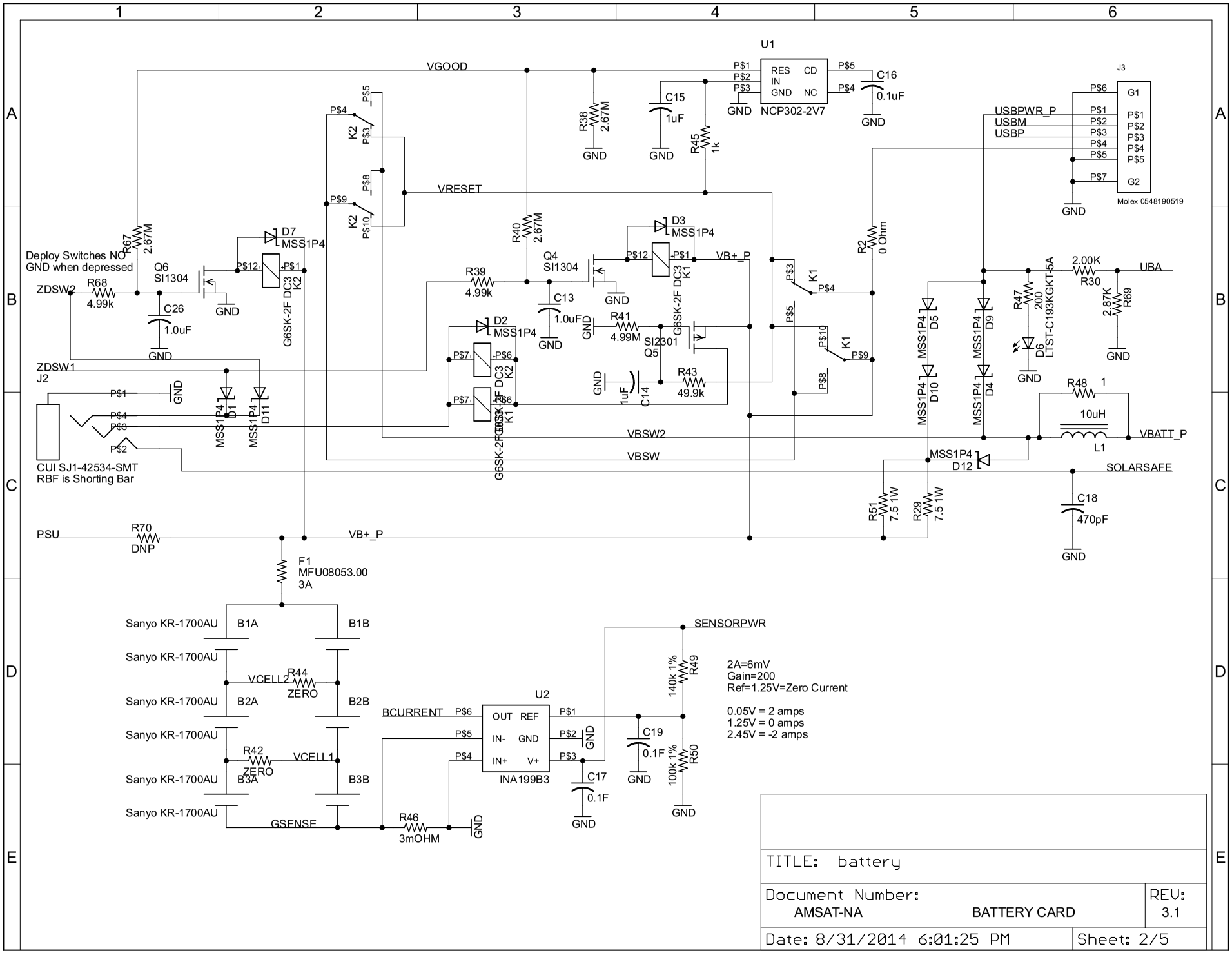
LEGEND

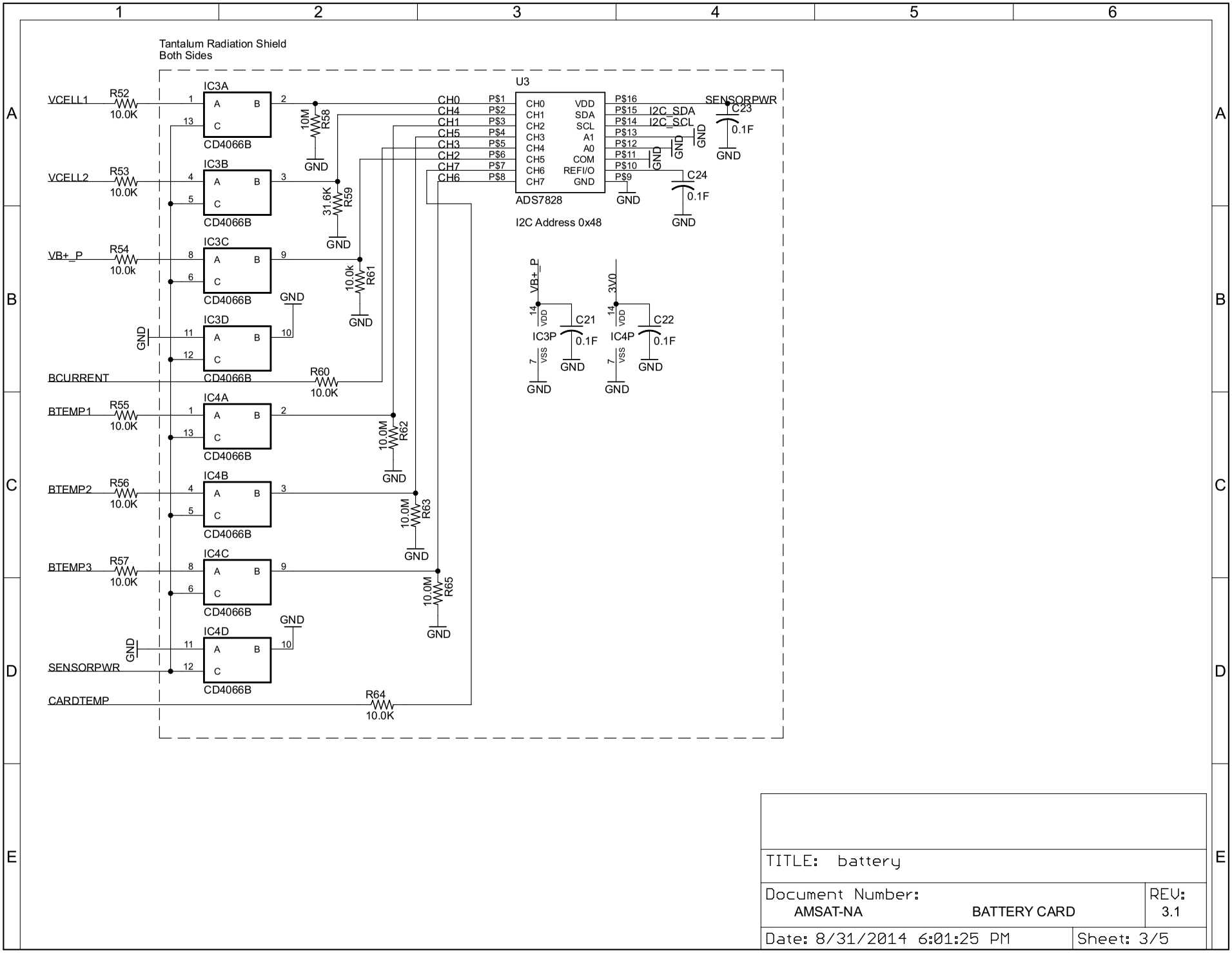
System
- ANTENNAS
- EXPERIMENTS
- ALL
- PSU/BATT
- UMBILICAL
- RF

Connections
- CONNECTED IN USE
- CONNECTED NOT IN USE
- NOT CONNECTED NOT USED



TITLE: battery	
Document Number: AMSAT-NA BATTERY CARD	REV: 3.1
Date: 8/31/2014 6:01:25 PM	Sheet: 1/5

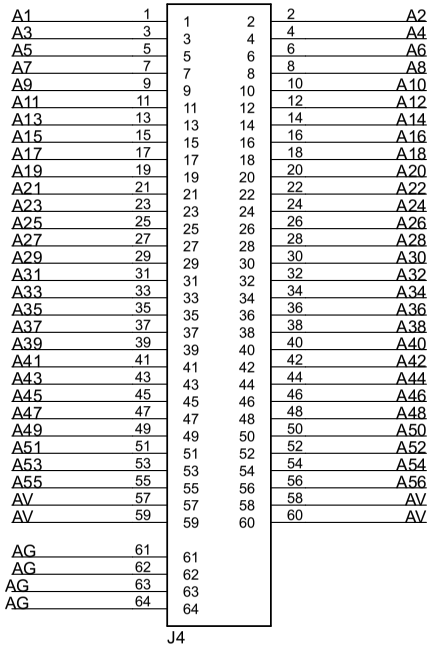

U1
NCP302-2V7
VGOOD
VRESET
C15
1uF
C16
0.1uF
R38
2.67M
R45
1k
R40
2.67M
R67
2.67M
R2
0 Ohm
J3
Molex 0548190519
USBPWR_P
USBM
USBP
Deploy Switches NC
GND when depressed
Q6
SI1304
R68
4.99k
C26
1.0uF
D7
MSS1P4
G6SK-2F DC3
K2
R39
4.99k
Q4
SI1304
C13
1.0uF
D3
MSS1P4
VB+_P
K1
R41
4.99M
SI2301
Q5
R43
49.9k
C14
1uF
D2
MSS1P4
ZDSW2
ZDSW1
J2
CUI SJ1-42534-SMT
RBF is Shorting Bar
D1
D11
MSS1P4
VBSW2
VBSW
D5
D9
D10
D4
R47
200
D6
LTST-C193KGKT-5A
2.00K
R30
2.87K
R69
UBA
R48
1
10uH
L1
VBATT_P
D12
SOLARSAFE
R51
7.5 1W
R29
7.5 1W
C18
470pF
PSU
R70
DNP
F1
MFU08053.00
3A
Sanyo KR-1700AU
B1A
B1B
B2A
B2B
B3A
B3B
R44
ZERO
R42
ZERO
VCELL2
VCELL1
GSENSE
R46
3mOHM
U2
INA199B3
BCURRENT
SENSORPWR
R49
140k 1%
R50
100k 1%
C19
0.1F
C17
0.1F
2A=6mV
Gain=200
Ref=1.25V=Zero Current
0.05V = 2 amps
1.25V = 0 amps
2.45V = -2 amps
TITLE: battery
Document Number:
AMSAT-NA
BATTERY CARD
REV:
3.1
Date: 8/31/2014 6:01:25 PM
Sheet: 2/5



TITLE:	battery
Document Number: AMSAT-NA BATTERY CARD	REV: 3.1
Date: 8/31/2014 6:01:25 PM	Sheet: 3/5

TOP

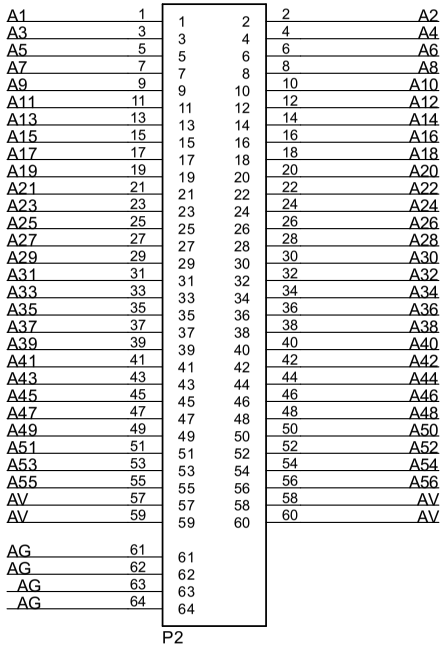
QTH-030-02-L-D-A



J4

BOTTOM

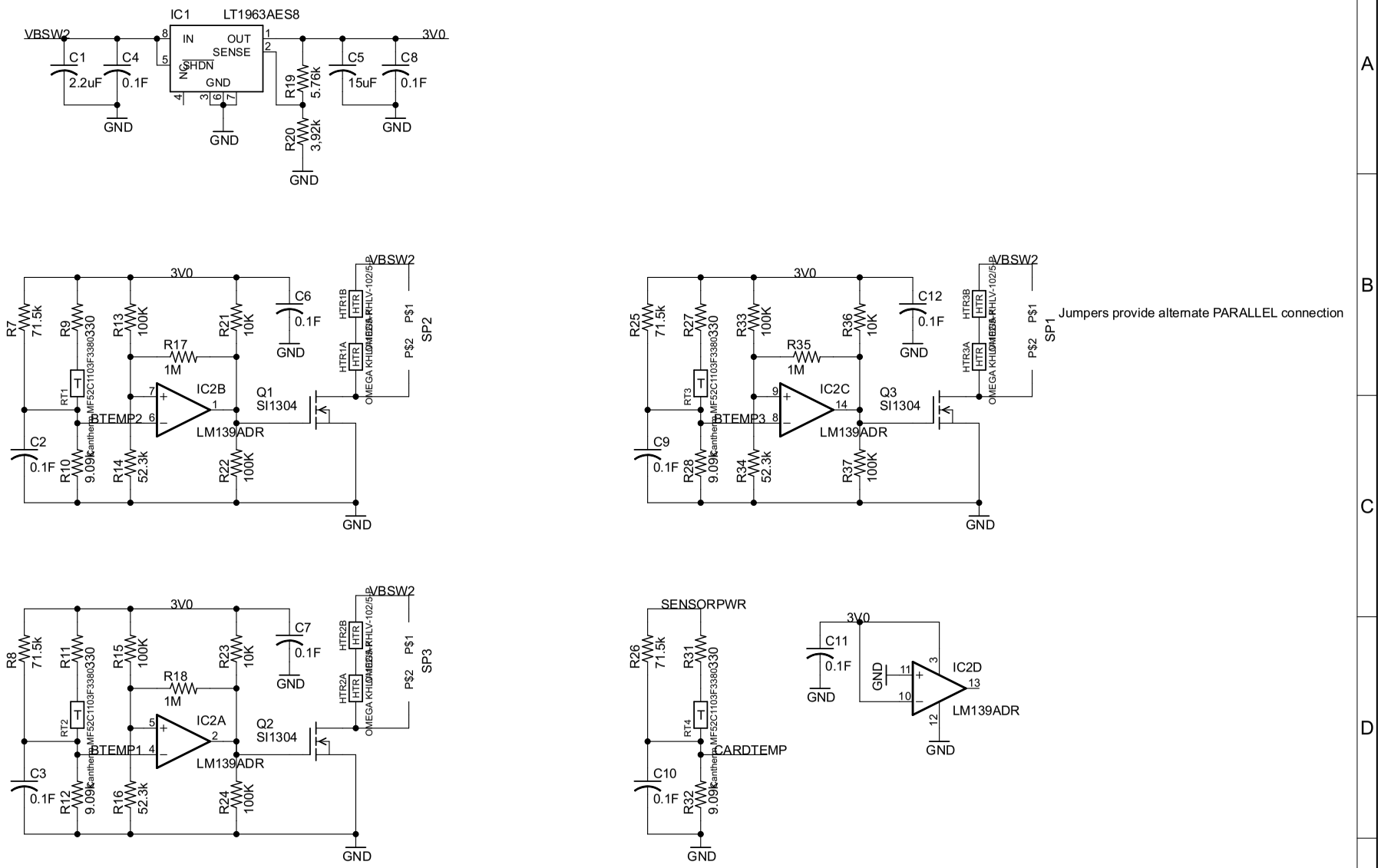
QSH-030-02-L-D-A



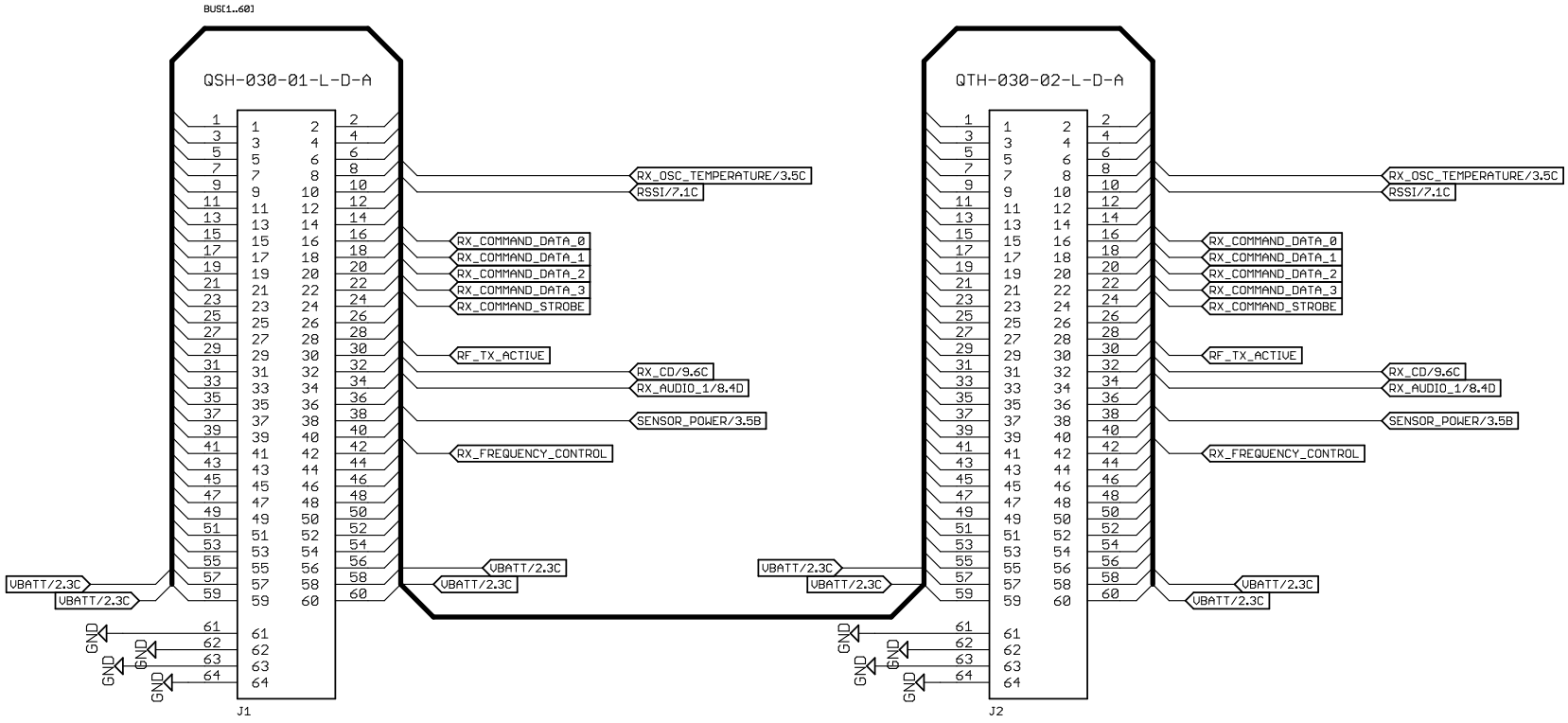
P2

Battery 2 Connector PCA

TITLE: battery		
Document Number: AMSAT-NA BATTERY CARD		REV: 3.1
Date: 8/31/2014 6:01:25 PM	Sheet: 4/5	


IC1 LT1963AES8
VBSW2
3V0
C1 2.2uF
C4 0.1F
C5 15uF
C8 0.1F
R19 5.76k
R20 3.92k
GND
3V0
VBSW2
R7 71.5k
R9 330
R13 100K
R17 1M
R21 10K
C6 0.1F
RT1 MF52C1103F3380
BTEMP2
IC2B
LM139ADR
Q1 SI1304
HTR1B
HTR1A
OMEGA KHLV-102/5
SP2
C2 0.1F
R10 9.09k
R14 52.3k
R22 100K
R25 71.5k
R27 330
R33 100K
R35 1M
R36 10K
C12 0.1F
RT3 MF52C1103F3380
BTEMP3
IC2C
Q3 SI1304
HTR3B
HTR3A
SP1
Jumpers provide alternate PARALLEL connection
C9 0.1F
R28 9.09k
R34 52.3k
R37 100K
R8 71.5k
R11 330
R15 100K
R18 1M
R23 10K
C7 0.1F
RT2 MF52C1103F3380
BTEMP1
IC2A
Q2 SI1304
HTR2B
HTR2A
SP3
C3 0.1F
R12 9.09k
R16 52.3k
R24 100K
SENSORPWR
R26 71.5k
R31 330
RT4 MF52C1103F3380
CARDTEMP
C10 0.1F
R32 9.09k
C11 0.1F
IC2D
LM139ADR
TITLE: battery
Document Number: AMSAT-NA
BATTERY CARD
REV: 3.1
Date: 8/31/2014 6:01:25 PM
Sheet: 5/5

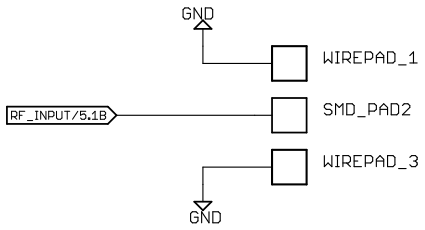
RF Receiver Bus Pin Assignments Version 2.95



BOTTOM (-Z)

TOP (+Z)

Thru-Hole/SMD Pads for COAX



TP32
Common Ground
For Testing

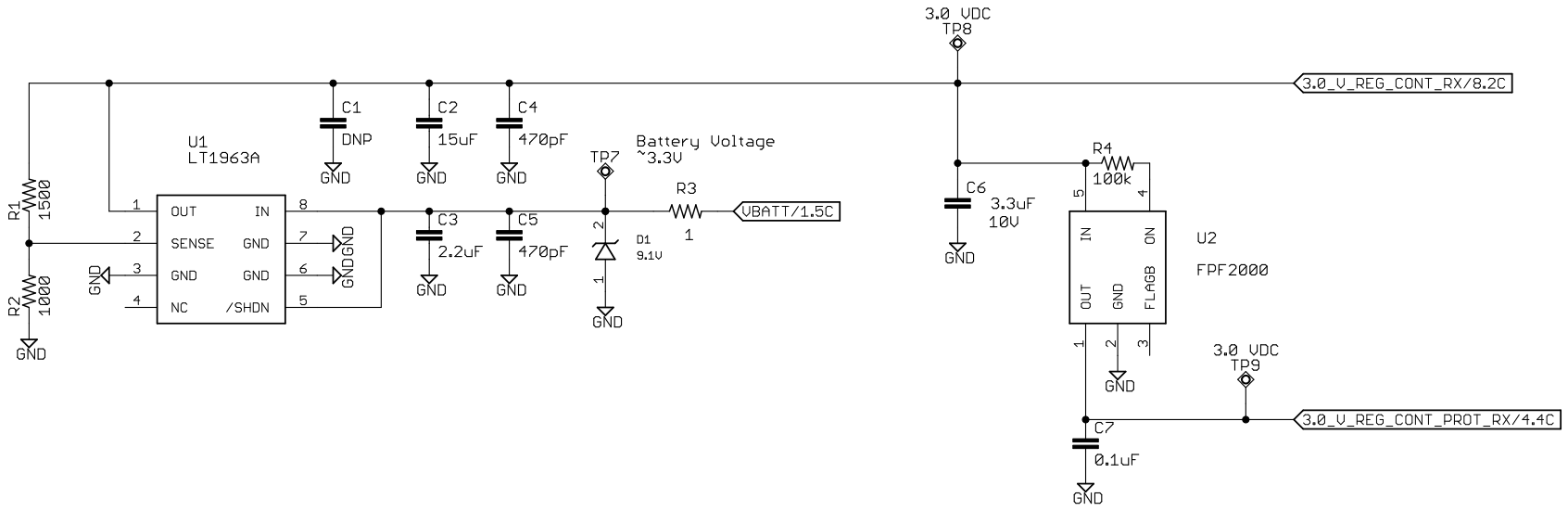
Keystone Electronics
5015

GND

Bus Connectors

TITLE: Fox-1 Receiver		
Document Number: AMSAT-NA FOX-1 RX		REV: 2.00
Date: 9/13/2014 1:11:19 AM	Sheet: 1/9	

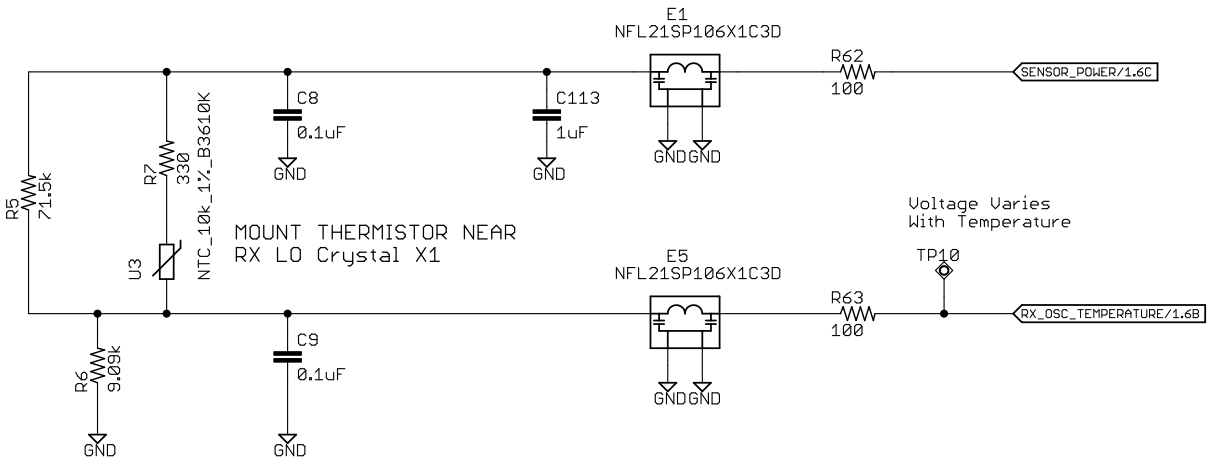
DWG: K4OZS



Receiver Power Conditioning

TITLE: Fox-1 Receiver		
Document Number: AMSAT-NA FOX-1 RX		REV: 2.00
Date: 9/13/2014 1:11:19 AM	Sheet: 2/9	

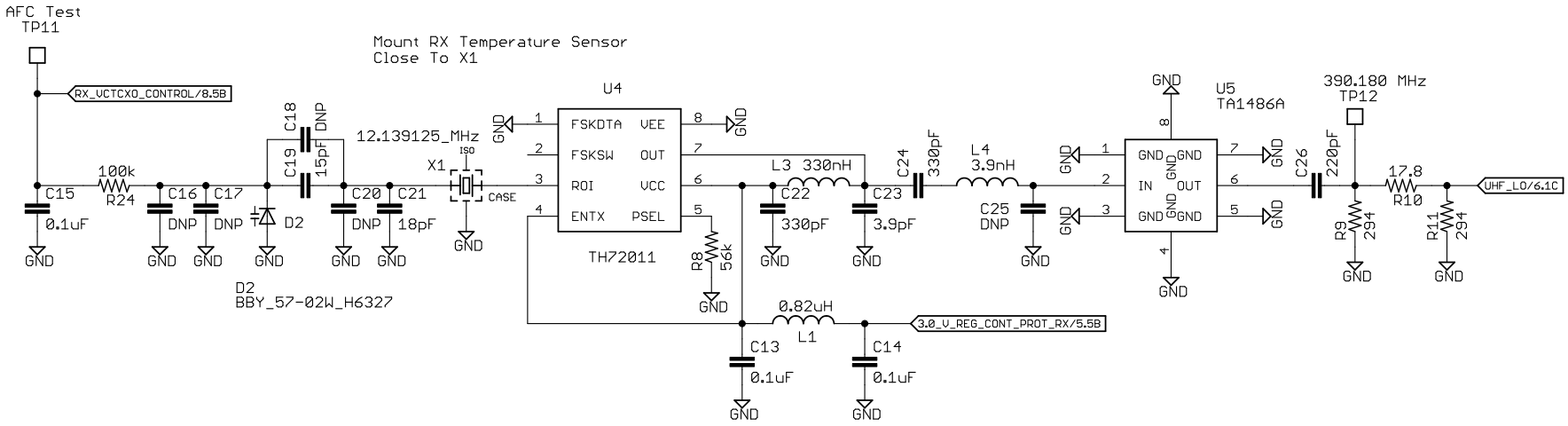
DWG: K4OZS



RX Temperature Sensor

TITLE: Fox-1 Receiver		
Document Number: AMSAT-NA FOX-1 RX		REV: 2.00
Date: 9/13/2014 1:11:19 AM	Sheet: 3/9	

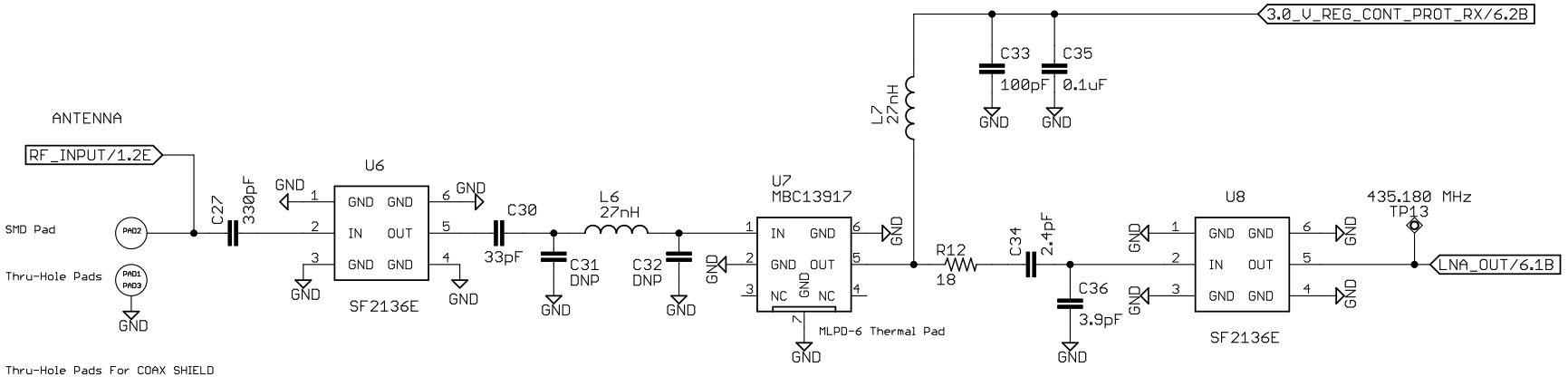
DWG: K4OZS



UHF Local Oscillator

TITLE: Fox-1 Receiver		
Document Number: AMSAT-NA	FOX-1 RX	REV: 2.00
Date: 9/13/2014 1:11:19 AM		Sheet: 4/9

DWG: K4OZS



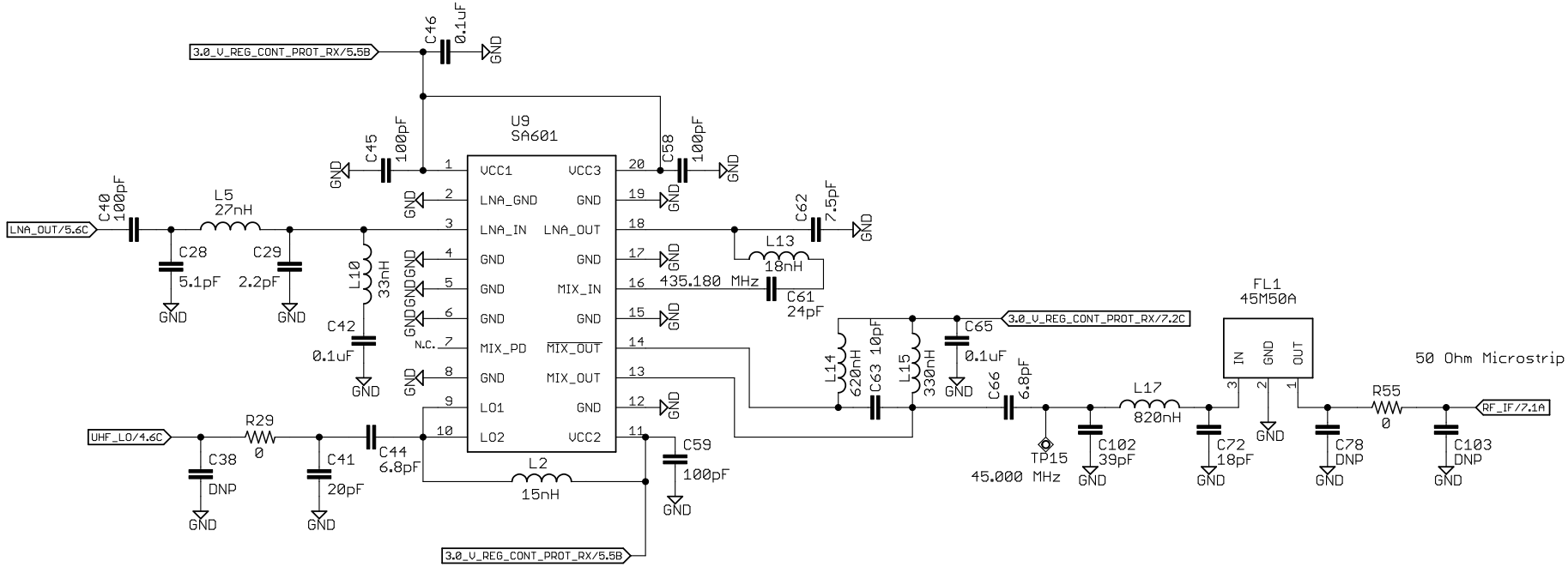
Thru-Hole Pads For COAX SHIELD
SMD Pad For COAX Center Conductor

MBC13917 Needs Radiation Shielding

Low-Noise Amplifier

TITLE: Fox-1 Receiver		
Document Number: AMSAT-NA FOX-1 RX		REV: 2.00
Date: 9/13/2014 1:11:19 AM	Sheet: 5/9	

DWG: K4OZS



SA601
Needs Radiation Shielding

Receiver LNA, First IF

TITLE: Fox-1 Receiver

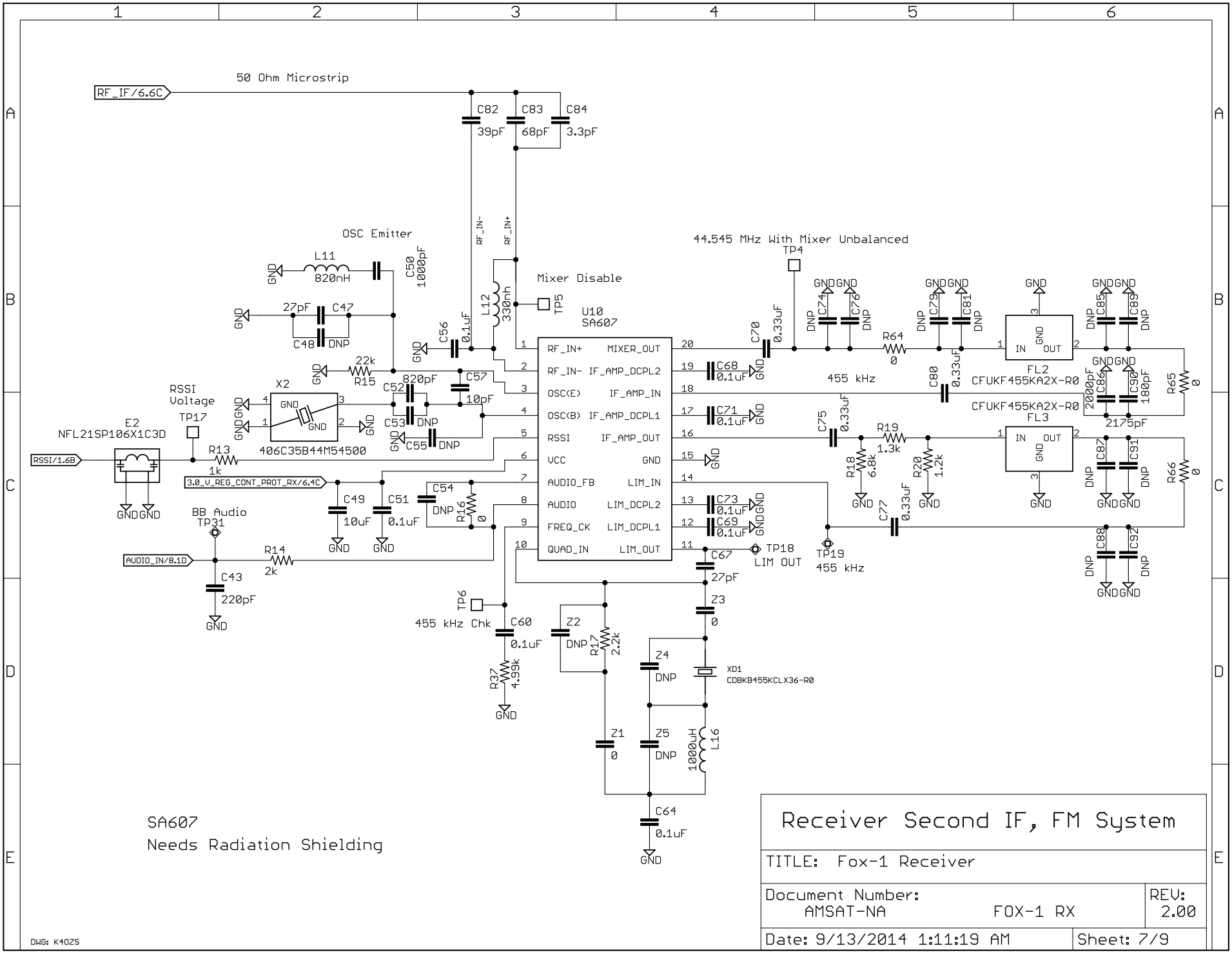
Document Number: AMSAT-NA FOX-1 RX

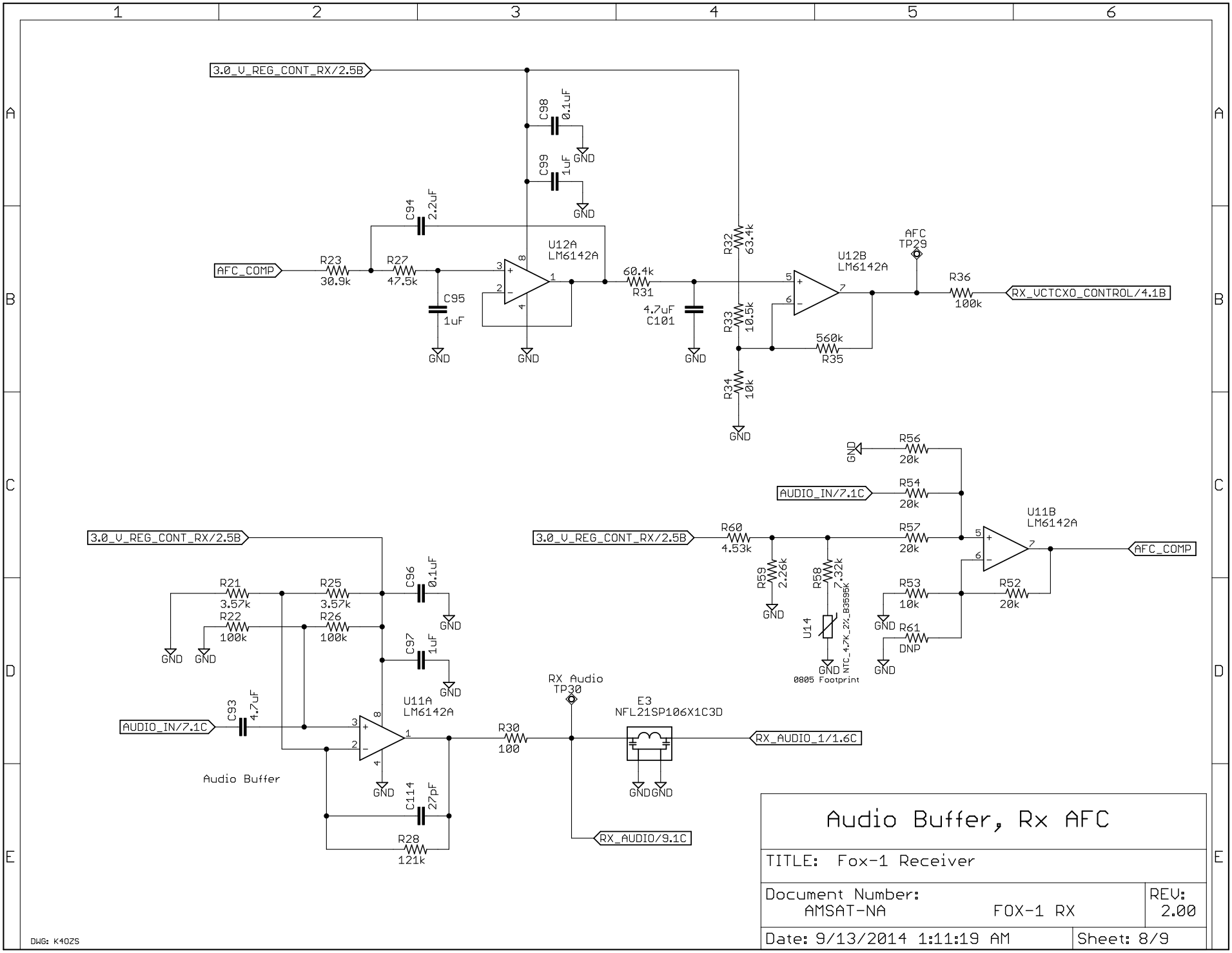
REV: 2.00

Date: 9/13/2014 1:11:19 AM

Sheet: 6/9

DWG: K4OZS

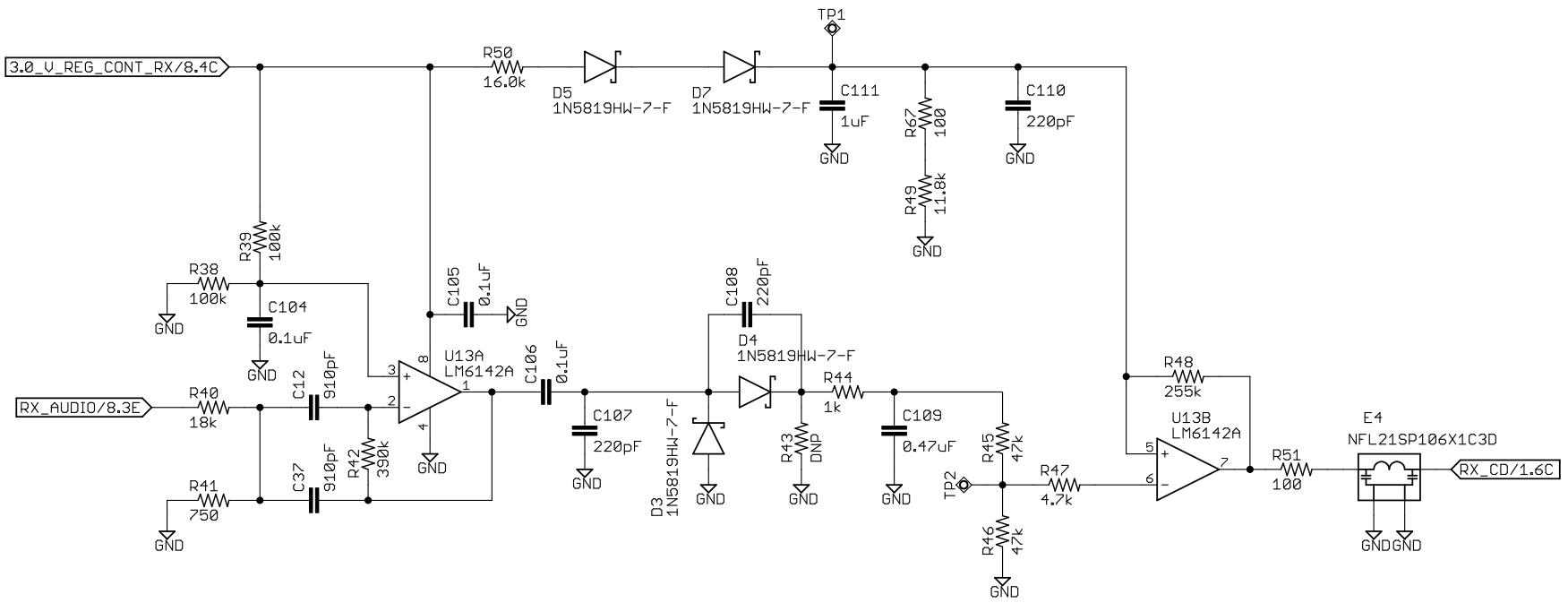

50 Ohm Microstrip
RF_IF/6.6C
C82 39pF
C83 68pF
C84 3.3pF
OSC Emitter
L11 820nH
C50 1000pF
27pF C47
C48 DNP
22k R15
C56 0.1uF
L12 330nh
RF_IN-
RF_IN+
Mixer Disable
TP5
U10 SA607
RF_IN+ MIXER_OUT
RF_IN- IF_AMP_DCPL2
OSC(E) IF_AMP_IN
OSC(B) IF_AMP_DCPL1
RSSI IF_AMP_OUT
VCC GND
AUDIO_FB LIM_IN
AUDIO LIM_DCPL2
FREQ_CK LIM_DCPL1
QUAD_IN LIM_OUT
44.545 MHz With Mixer Unbalanced
TP4
C70 0.33uF
R64 0
C80 0.33uF
455 kHz
FL2 CFUKF455KA2X-R0
FL3 CFUKF455KA2X-R0
2000pF C86
C90 180pF
2175pF
R65 0
R66 0
C75 0.33uF
R19 1.3k
R18 6.8k
R20 1.2k
C77 0.33uF
C87 C91 C88 C92 DNP
C68 0.1uF
C71 0.1uF
C73 0.1uF
C69 0.1uF
C67 27pF
TP18 LIM OUT
TP19 455 kHz
RSSI Voltage
TP17
X2
406C35B44M54500
820pF C52
C57 10pF
C53 DNP
C55 DNP
E2 NFL21SP106X1C3D
RSSI/1.6B
R13 1k
3.0_V_REG_CONT_PROT_RX/6.4C
C49 10uF
C51 0.1uF
C54 DNP
R16 0
BB Audio TP31
AUDIO_IN/8.1D
R14 2k
C43 220pF
TP6
455 kHz Chk
C60 0.1uF
R37 4.99k
Z2 DNP
R17 2.2k
Z3 0
Z4 DNP
XD1 CDBKB455KCLX36-R0
Z1 0
Z5 DNP
1000uH L16
C64 0.1uF
SA607
Needs Radiation Shielding
Receiver Second IF, FM System
TITLE: Fox-1 Receiver
Document Number: AMSAT-NA FOX-1 RX
REV: 2.00
Date: 9/13/2014 1:11:19 AM
Sheet: 7/9
DWG: K4OZS



Audio Buffer, Rx AFC

TITLE: Fox-1 Receiver		
Document Number: AMSAT-NA	FOX-1 RX	REV: 2.00
Date: 9/13/2014 1:11:19 AM		Sheet: 8/9

DWG: K4OZS



Noise Squelch, COR

TITLE: Fox-1 Receiver

Document Number: AMSAT-NA FOX-1 RX

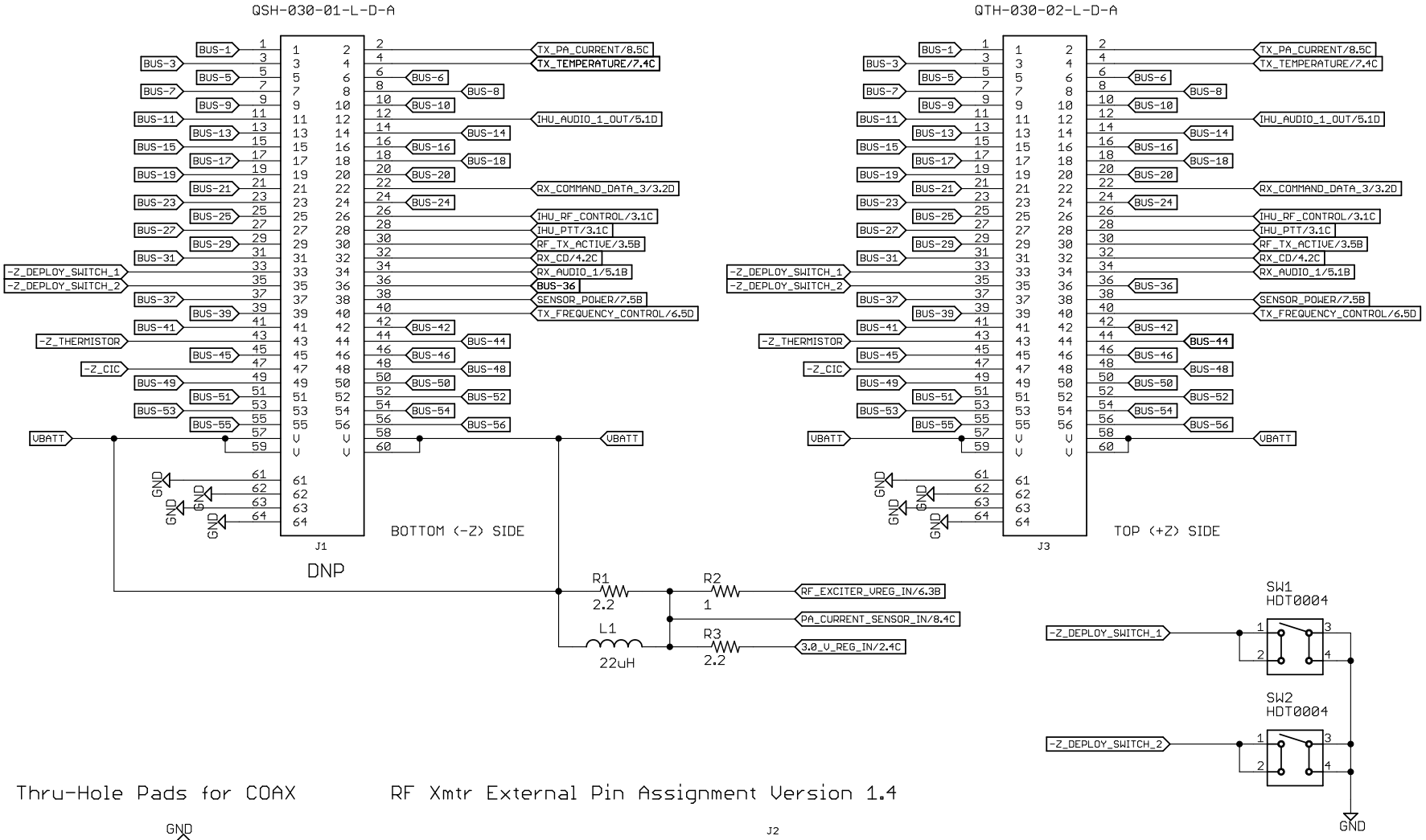
REV: 2.00

Date: 9/13/2014 1:11:19 AM

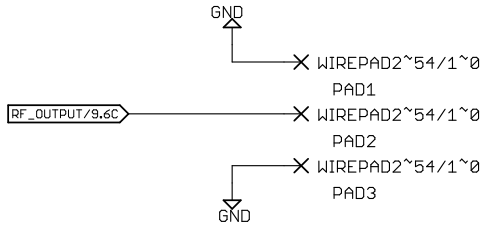
Sheet: 9/9

DWG: K4OZS

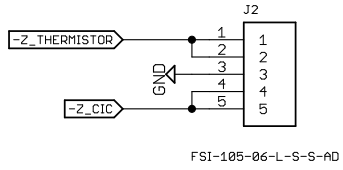
RF Xmtr Bus Pin Assignment Version 2.8 From SDS Version 3.5



Thru-Hole Pads for COAX



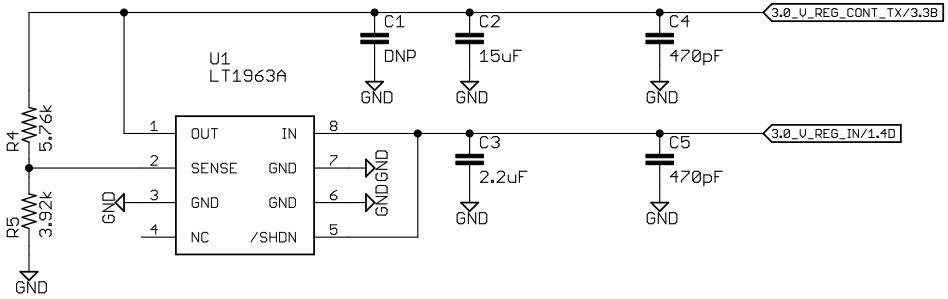
RF Xmtr External Pin Assignment Version 1.4



DWG: K4OZS

Bus And External Connectors

TITLE: Transmitter V3		
Document Number: AMSAT-NA	FOX-1 TX V3	REV: 3.01
Date: 9/15/2014 5:53:59 PM		Sheet: 1/9



TX Power Supply

TITLE: Transmitter V3

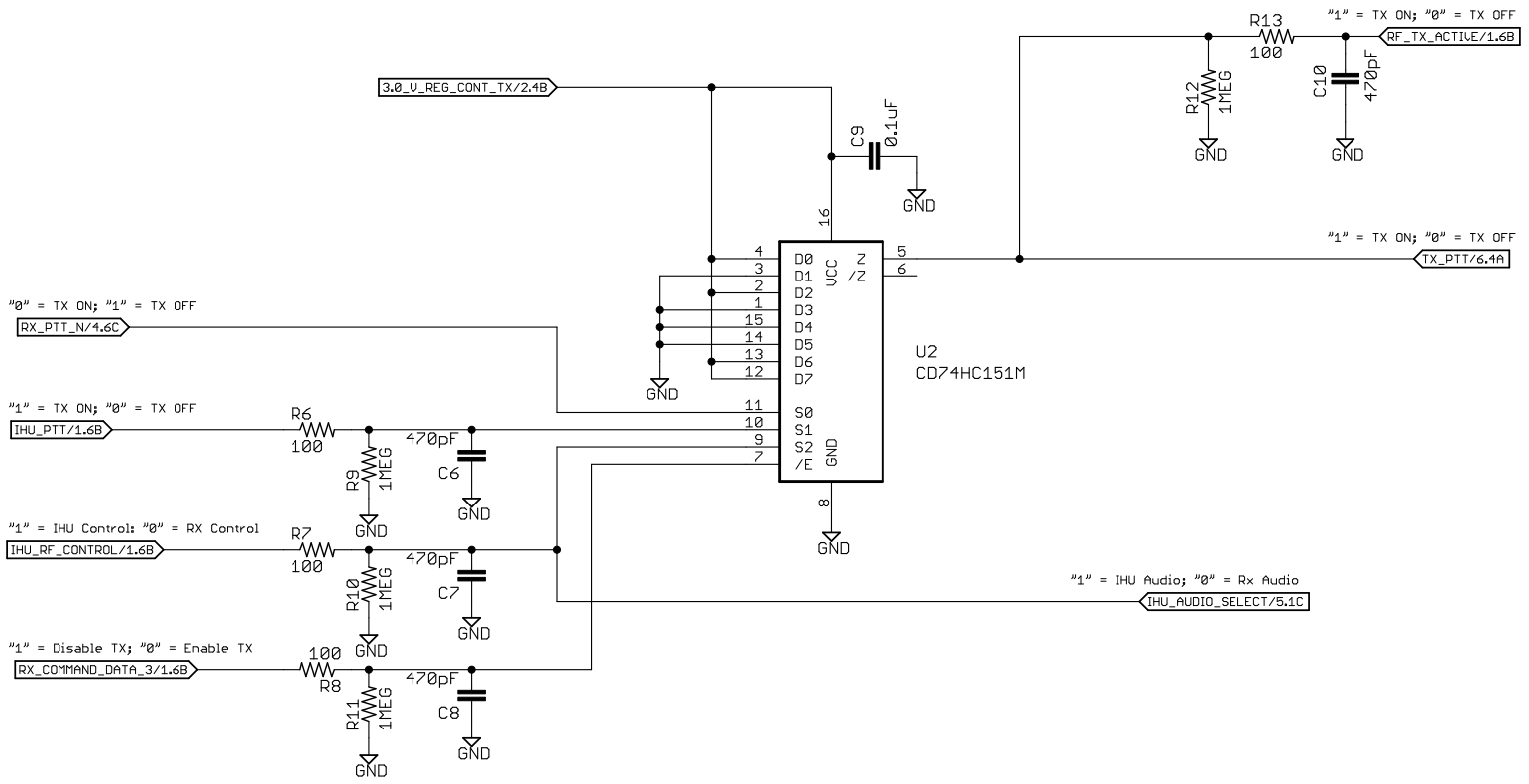
Document Number: AMSAT-NA FOX-1 TX V3

REV: 3.01

Date: 9/15/2014 5:53:59 PM

Sheet: 2/9

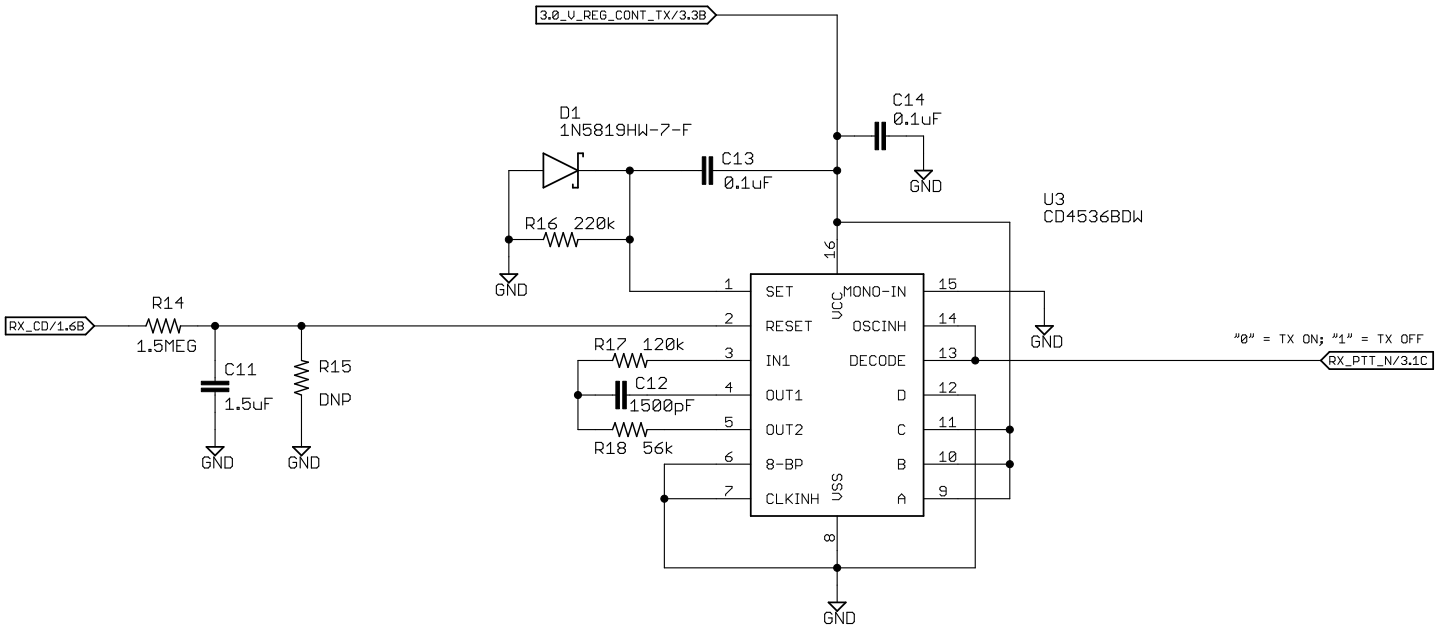
DWG: K4OZS



TX Keying Logic

TITLE: Transmitter V3		
Document Number: AMSAT-NA	FOX-1 TX V3	REV: 3.01
Date: 9/15/2014 5:53:59 PM		Sheet: 3/9

DWG: K4OZS

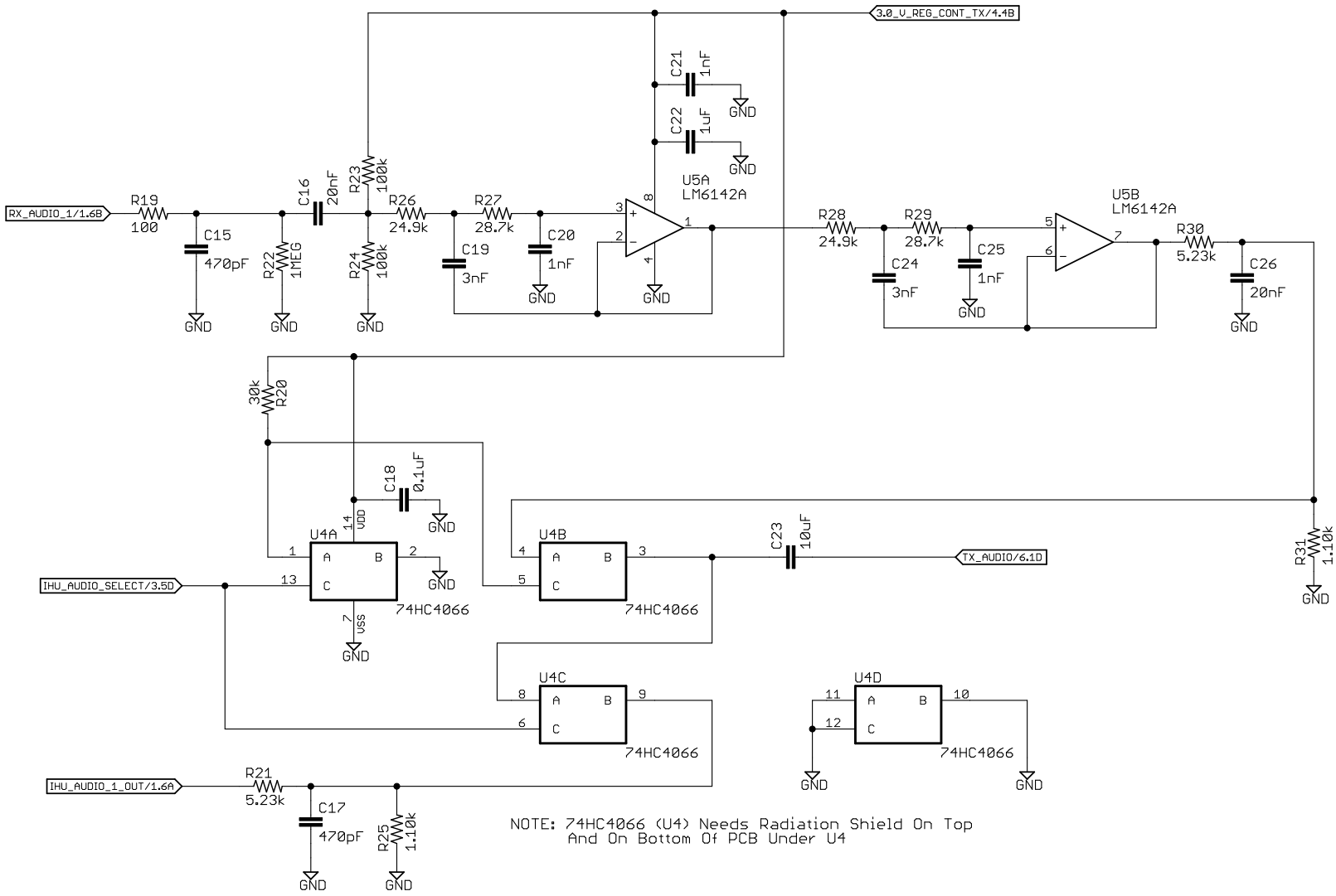


C12:
Select By Test
For Hang Timer Duration

TX Hang Timer

TITLE: Transmitter V3		
Document Number: AMSAT-NA	FOX-1 TX V3	REV: 3.01
Date: 9/15/2014 5:53:59 PM		Sheet: 4/9

DWG: K4OZS

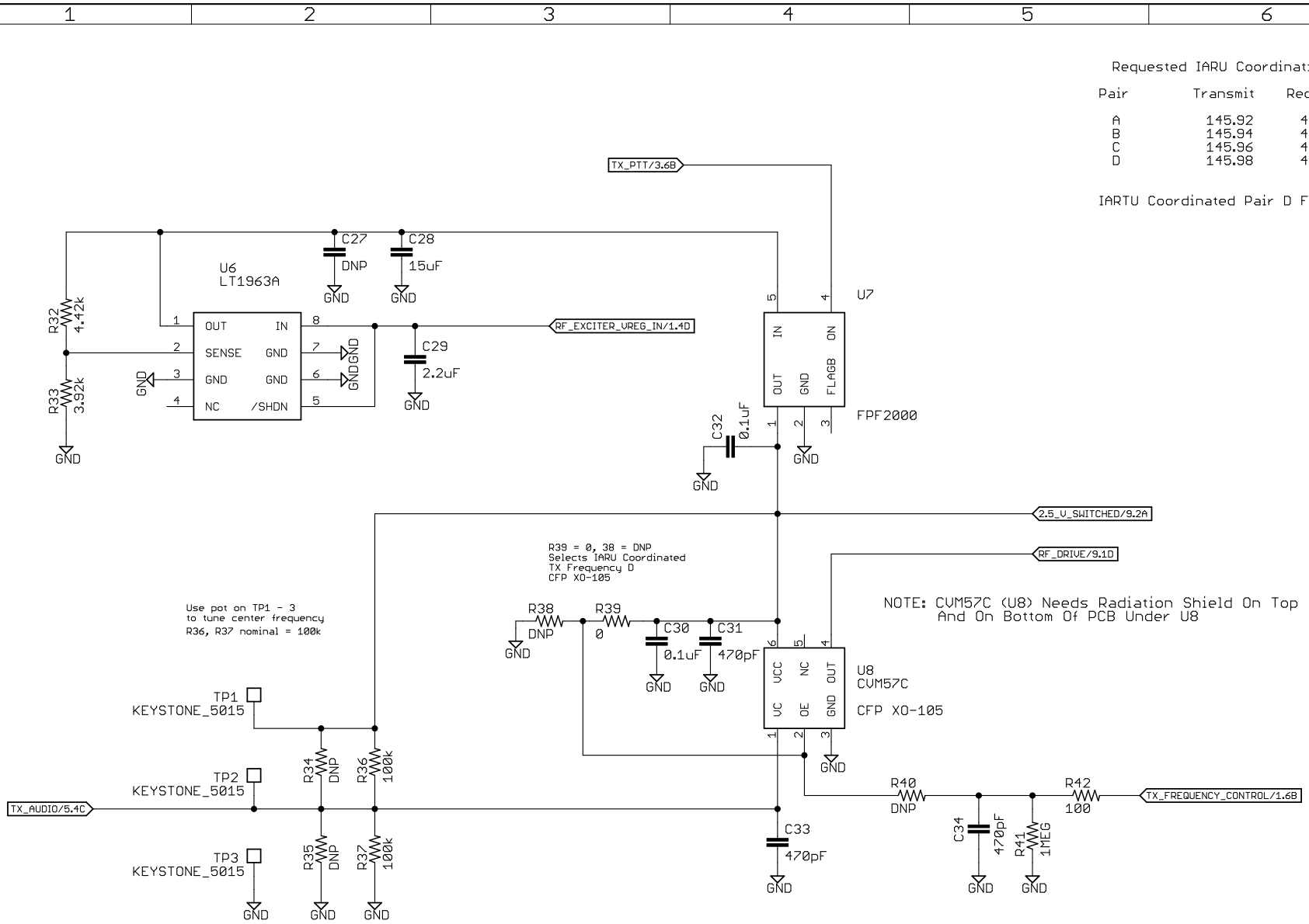


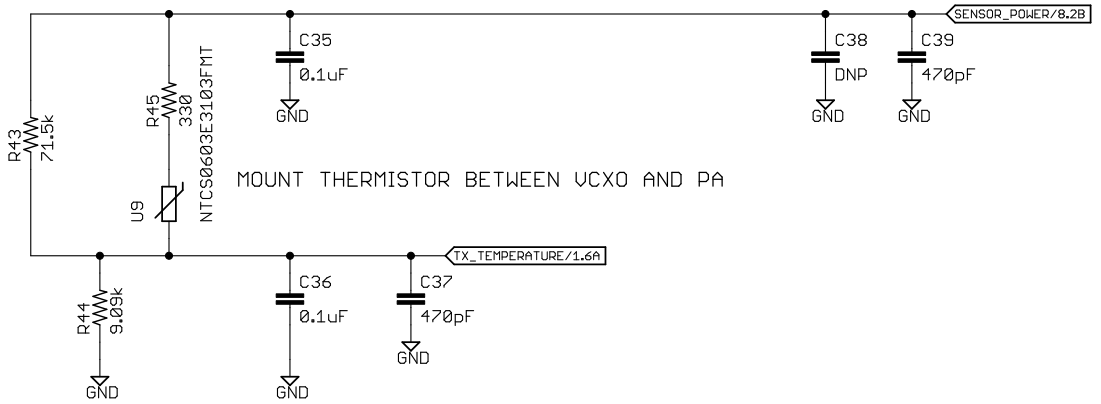
NOTE: 74HC4066 (U4) Needs Radiation Shield On Top
And On Bottom Of PCB Under U4

TX Baseband Audio Processing

TITLE: Transmitter V3		
Document Number: AMSAT-NA	FOX-1 TX V3	REV: 3.01
Date: 9/15/2014 5:53:59 PM		Sheet: 5/9

DWG: K4OZS


Requested IARU Coordination:
Pair Transmit Receive
A 145.92 435.12
B 145.94 435.14
C 145.96 435.16
D 145.98 435.18
IARTU Coordinated Pair D For FOX-1
TX_PTT/3.6B
U6
LT1963A
OUT
SENSE
GND
GND
NC
IN
GND
GND
/SHDN
C27
DNP
C28
15uF
C29
2.2uF
R32
4.42k
R33
3.92k
RF_EXCITER_VREG_IN/1.4D
U7
IN
OUT
GND
ON
FLAGB
FPF2000
C32
0.1uF
2.5_V_SWITCHED/9.2A
RF_DRIVE/9.1D
R39 = 0, 38 = DNP
Selects IARU Coordinated
TX Frequency D
CFP XO-105
NOTE: CVM57C (U8) Needs Radiation Shield On Top
And On Bottom Of PCB Under U8
Use pot on TP1 - 3
to tune center frequency
R36, R37 nominal = 100k
R38
DNP
R39
0
C30
0.1uF
C31
470pF
U8
CVM57C
CFP XO-105
VCC
NC
OUT
VC
OE
GND
TP1
KEYSTONE_5015
TP2
KEYSTONE_5015
TP3
KEYSTONE_5015
R34
DNP
R36
100k
R35
DNP
R37
100k
TX_AUDIO/5.4C
C33
470pF
R40
DNP
R42
100
TX_FREQUENCY_CONTROL/1.6B
C34
470pF
R41
1MEG
R38 = 0, R39 = DNP
Selects IARU Coordinated
TX Frequency C
CFP XO-105
DWG: K4OZS
TX RF Exciter
TITLE: Transmitter V3
Document Number:
AMSAT-NA
FOX-1 TX V3
REV:
3.01
Date: 9/15/2014 5:53:59 PM
Sheet: 6/9

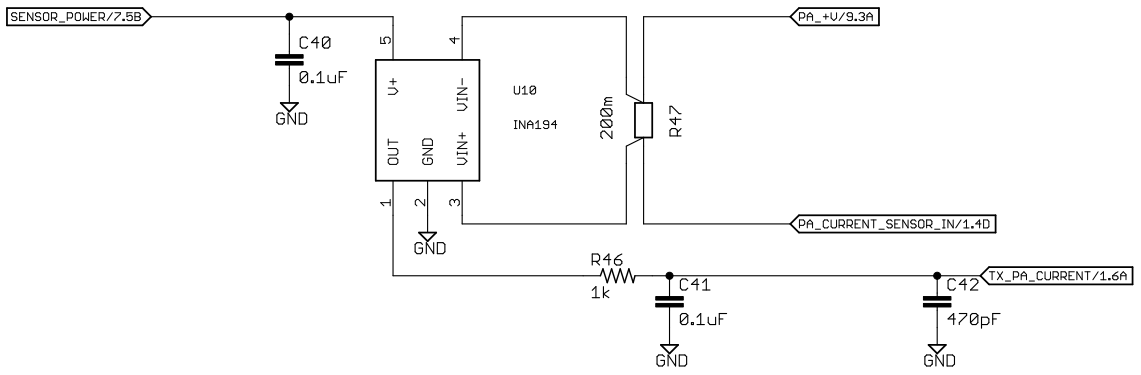


1	2	3	4	5	6

TX Temperature Sensor

TITLE: Transmitter V3		
Document Number: AMSAT-NA	FOX-1 TX V3	REV: 3.01
Date: 9/15/2014 5:53:59 PM		Sheet: 7/9

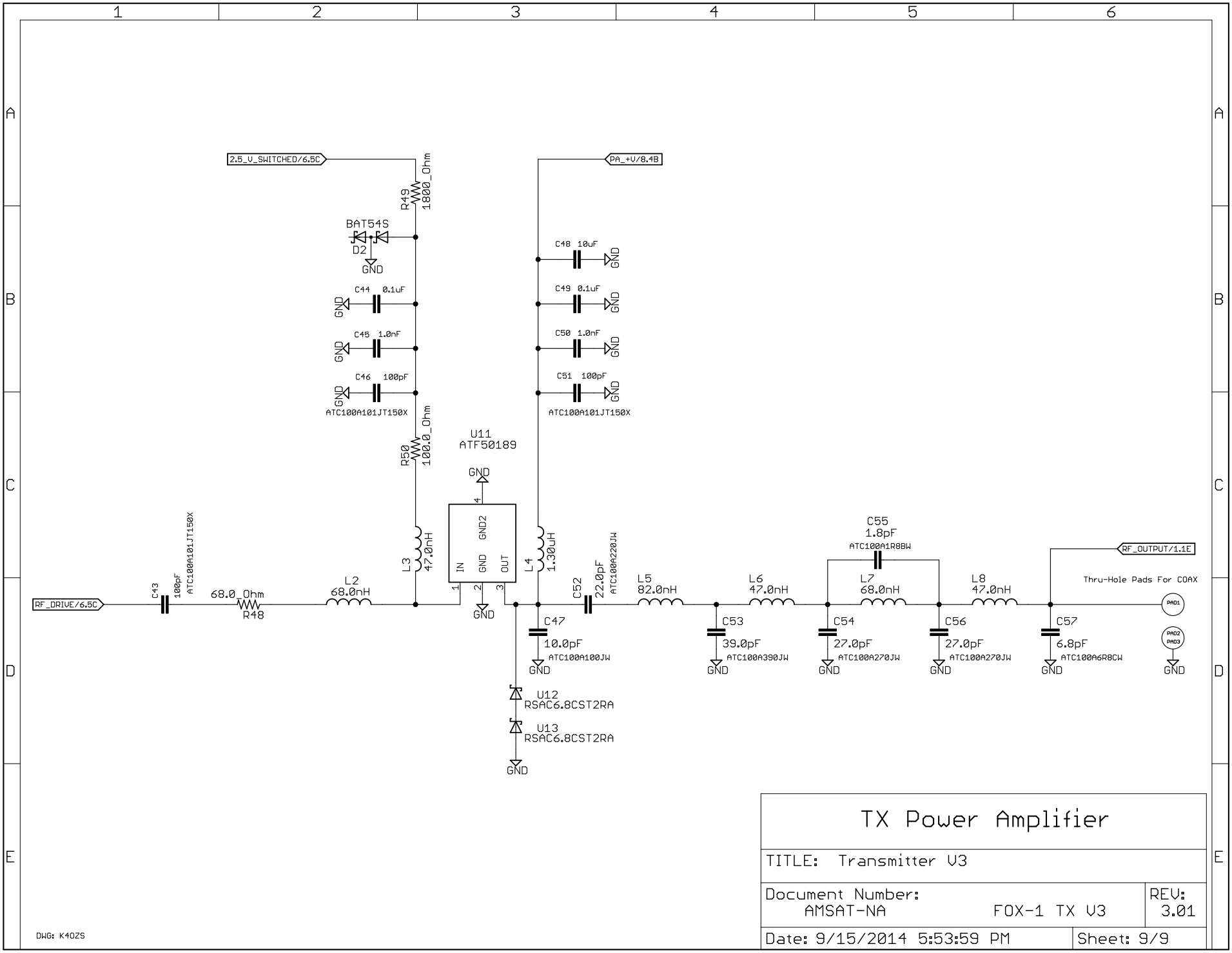
DWG: K4OZS



PA Current Sensor

TITLE: Transmitter V3		
Document Number: AMSAT-NA	FOX-1 TX V3	REV: 3.01
Date: 9/15/2014 5:53:59 PM		Sheet: 8/9

DWG: K4OZS



TX Power Amplifier

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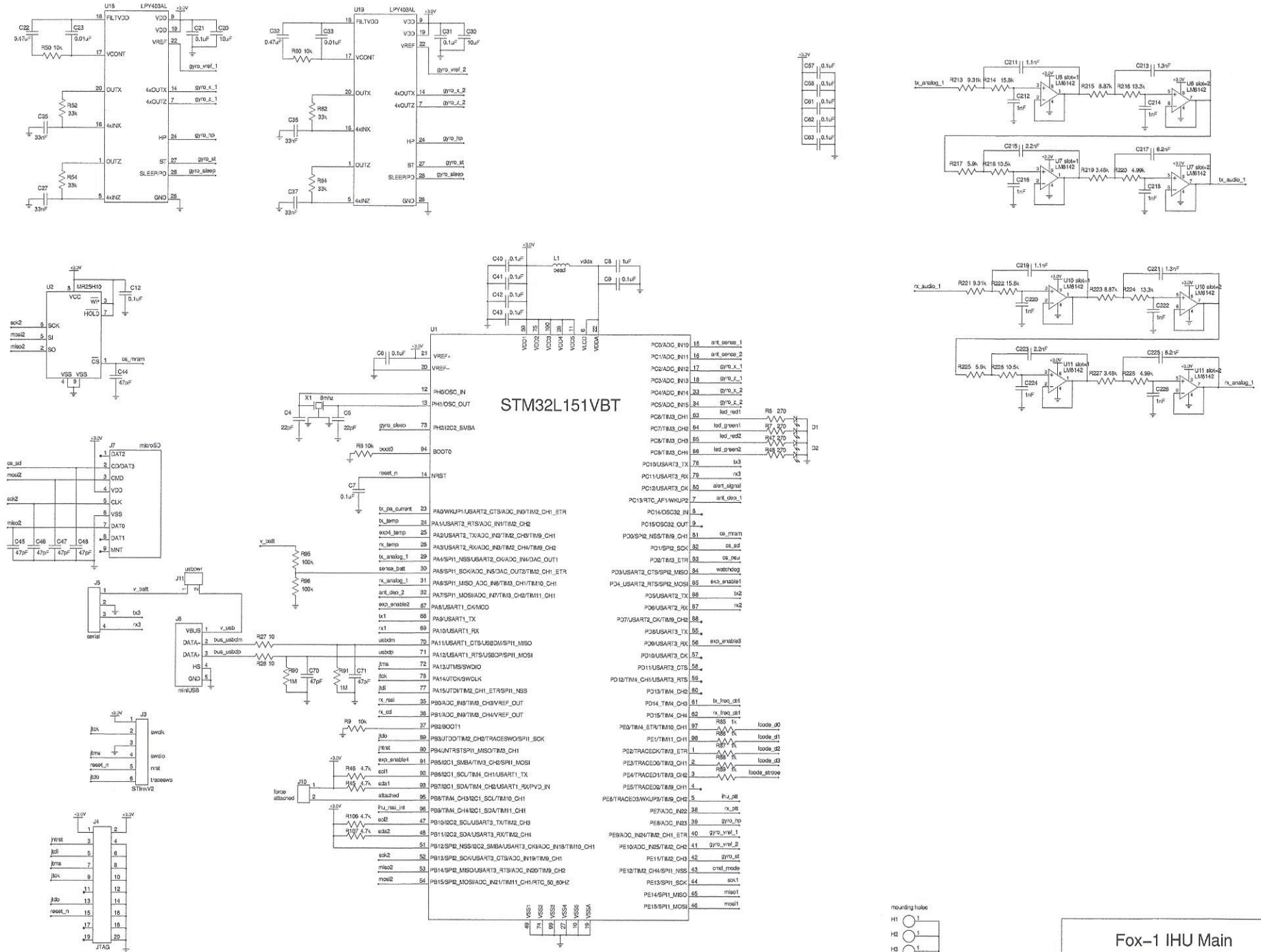

Fox-1 IHU Main

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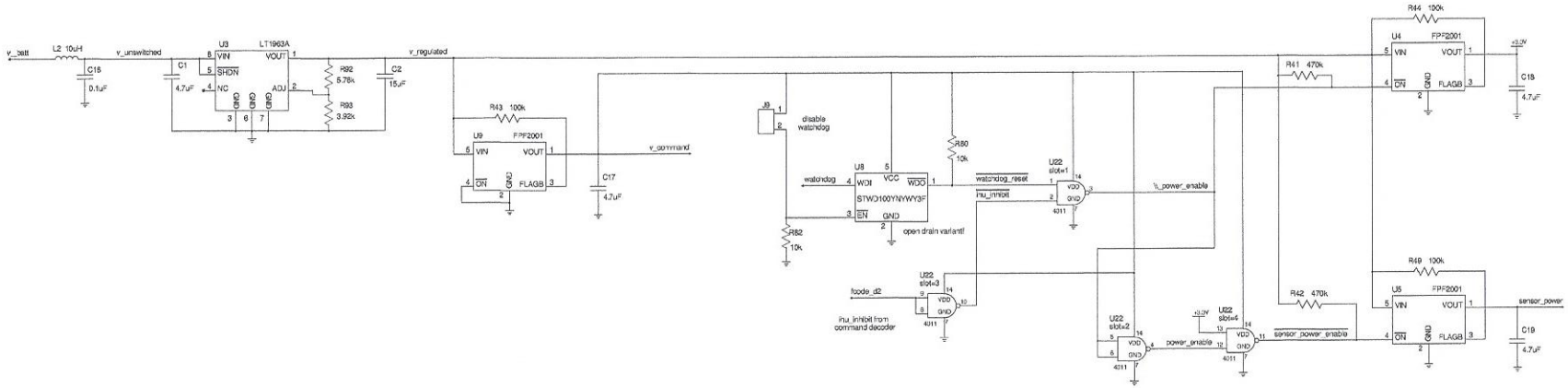

Fox-1 IHU Power

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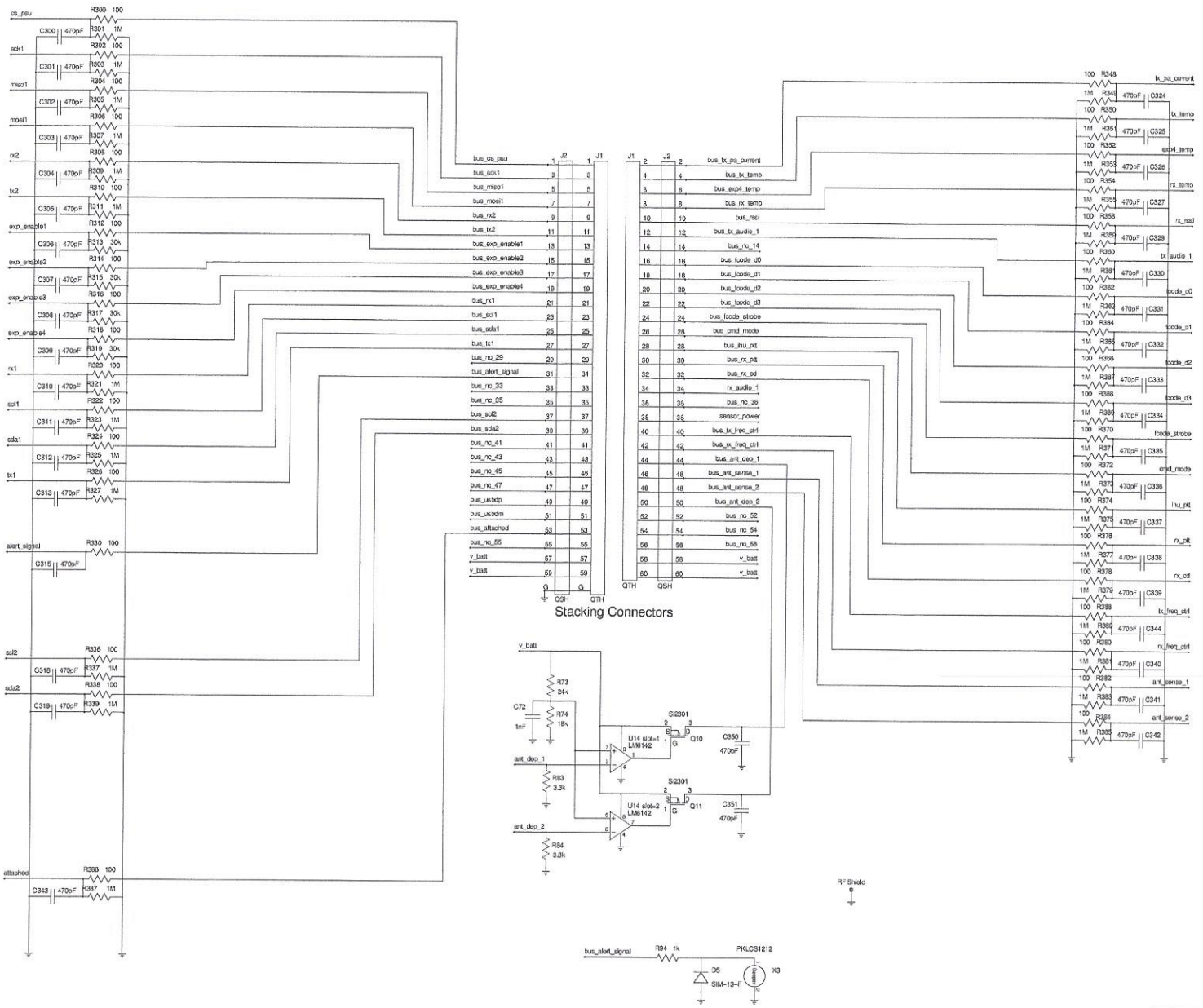

Fox–1 IHU Stacking Bus

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FILE: bus.sch PAGE 3 OF 3 REVISION: 3

Project URL: http://amsat.org

Date: October 2, 2015
Version: 1.1
Author: Bryce Salmi, KB1LQC

AMSAT Fox-1 Maximum Power Point Tracker

Introduction

The Radio Amateur Satellite Corporation, *AMSAT*, has designed and built a series of 1U Cubesats referred to as Fox-1. Starting with these 1U Cubesats, AMSAT will build up intellectual property to leverage onto future satellite designs. A requirement for the Fox-1 satellites is an efficient way to maximize power generation from solar cells with a scalable Maximum Power Point Tracker, *MPPT*. Based on the Fox-2 design originally conceived by the P13271 senior design team[1] at the Rochester Institute of Technology AMSAT has developed a radiation tolerant analog MPPT for use on the Fox-1 satellites. Lessons learned building the Fox-1 MPPT detailed in this document can also be rolled into any future Fox-2 MPPT design.

Document History

DATE	VERSION	SUMMARY
January 21, 2015	1.0	Initial creation of document
October 2, 2015	1.1	Updated with flight design

Document Scope

The purpose of this document is to clearly explain how the Fox-1 MPPT has been designed, how it operates, and to how any known failure modes or risks affect the spacecraft. Only PCB Revision 1.1 of the Fox-1 MPPT is detailed in this document. It also assumes a basic level of electrical knowledge and leaves some calculations up to the reader with reference material noted.

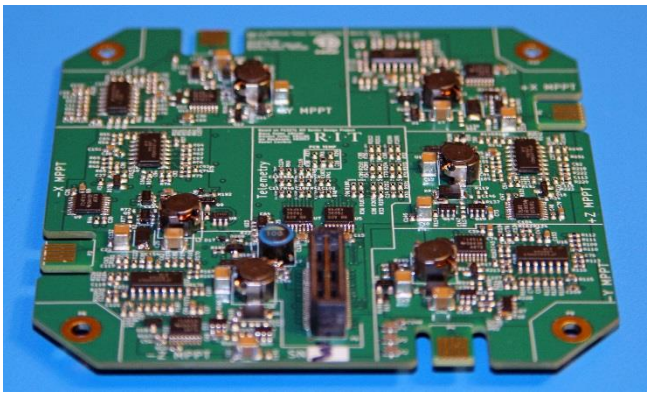

Figure 1: Fox-1 MPPT Rev 1.1

[1] Bryce Salmi (KB1LQC), Brenton Salmi (KB1LQD), Ian MacKenzie (KB3OCF), Dan Corriero

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Overview

The Fox-1 MPPT PCB contains six set-point constant voltage MPPT circuits[2] with a single MPPT dedicated to each side of the spacecraft. Every side of Fox-1 contains two Spectrolab UTJ solar cells connected in series. All six MPPTs are combined through ideal diodes which allows for power sharing as the satellite rotates in orbit. The common diode OR'd output node then delivers the combined power of all sufficiently illuminated solar panels to the spacecraft main voltage bus. The Fox-1 MPPT also contains a telemetry circuit able to communicate with the Internal Housekeeping Unit, *IHU*, via I^2C communications. It's important to note that each of the six MPPTs is a zero fault tolerant design.

Specifications

Parameter	Value	Units
Maximum Input Voltage	50	*Volts*
Minimum Input Voltage	3.6	*Volts*
Maximum Input Current (Per MPPT)	0.443	*Amperes*
Maximum Input Power (Per MPPT)	2.57	*Watts*
Maximum Output Current (Per MPPT)	0.780	*Amps @ 3.3V Vout*
Maximum Output Voltage	4.33V	*Volts*
Maximum Switching Efficiency	~88	*%*
Maximum Tracking Error	+-5	*%*
Temperature Range of Components	-40° to +125°	*Celsius*
Solar Cell Operating Temperature Range	-60° to +60°	*Celsius*

Table 1: Overall Fox-1 MPPT Specifications

Careful use of radiation tested components, shielding, and a stateless design in the critical MPPT feedback loops on Fox-1 has been implemented in order to promote a 5 year mission timeline and an estimated 30kRad TID exposure. The stateless design hardens the MPPT to Single Event Upsets, *SEU,* and Single Event Latch-ups, SEL, which are expected during the mission. Table 1 documents the general specifications achieved as supported by engineering bring-up data.

[2] http://cdn.intechopen.com/pdfs-wm/37984.pdf

Spectrolab UTJ Solar Cells

Fox-1 was designed for use with two SpectroLab UTJ solar cells in series on each solar panel with each cell having 27 cm^2 of area as shown in Figure 2. Table 11 in the Appendix shows the calculations of the maximum power point thermal drift. This information was used to design the MPPT as well as predict the amount of power available to Fox-1 at any panel temperature expected in orbit. The RTD measuring panel temperature is mounted to the back side of the solar panels out of direct sunlight.

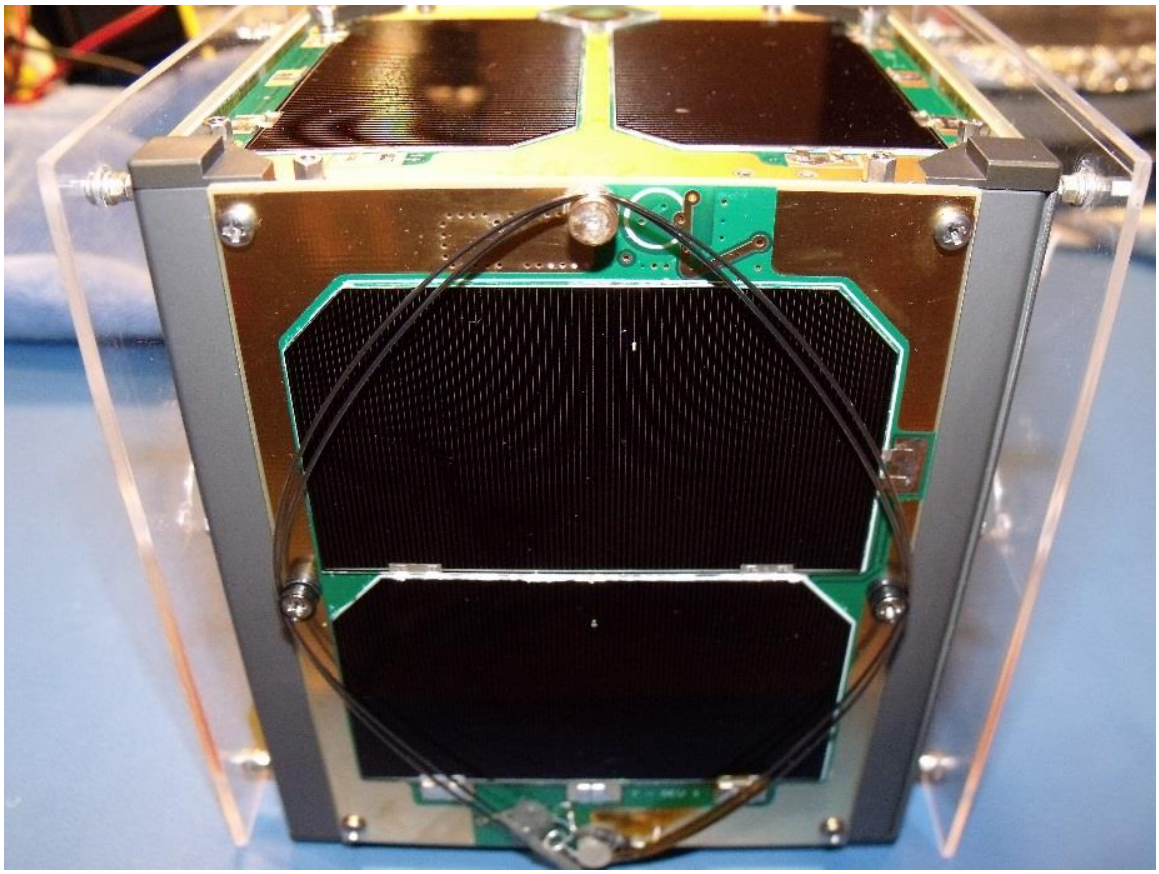


Figure 2: Solar panels on Fox-1, a stowed antenna is shown on the closest facing solar panel

MPPT PCB Configuration

PCB Block Diagram

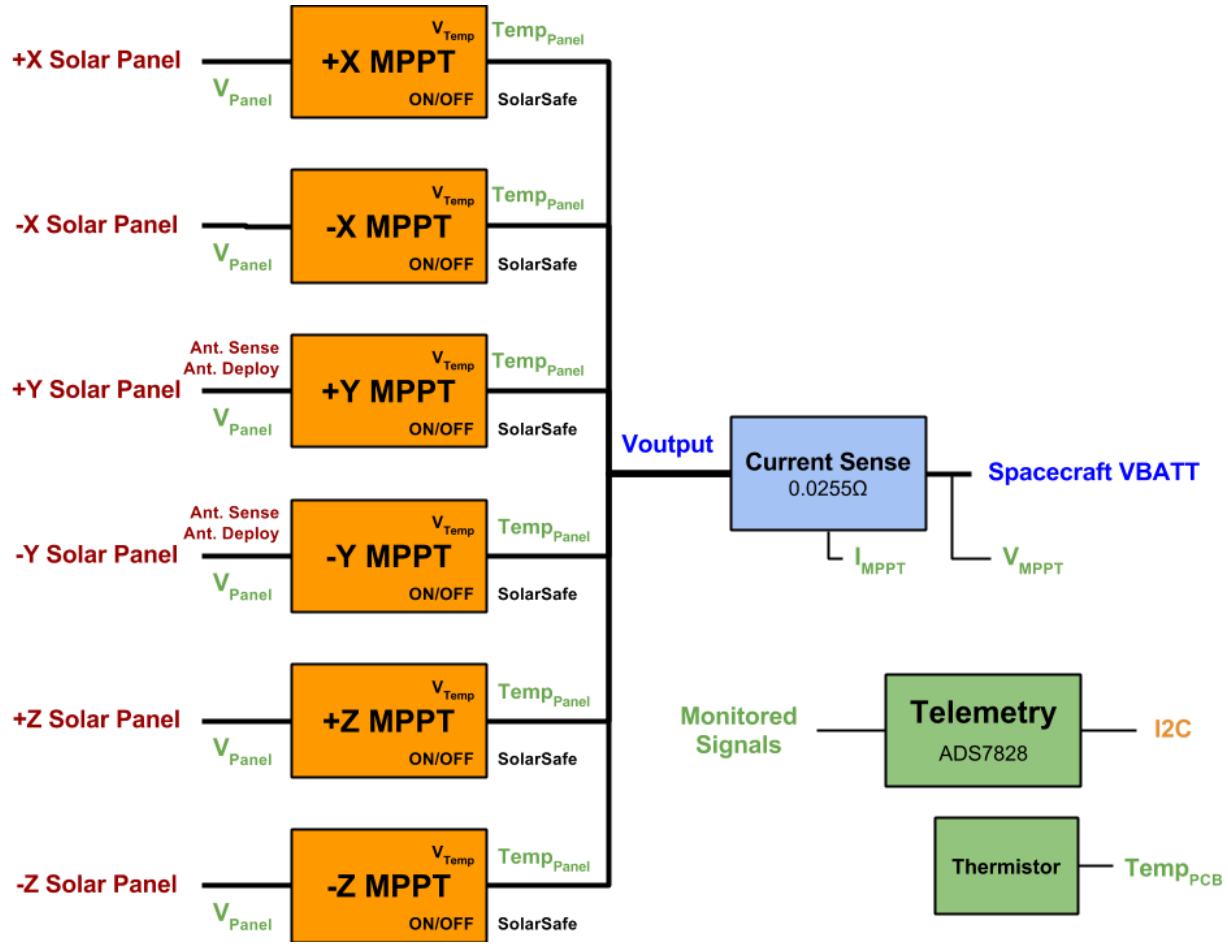


Figure 3: Fox-1 MPPT PCB block diagram containing six individual MPPT circuits combined together

Six Individual Maximum Power Point Trackers obtain power from their respective solar panels and if sufficient power is available then combine the generated power onto a common output node through ideal diodes. The combined power is then fed through a current sense circuit before being sent to the Fox-1 "VBATT" node to power the satellite and charge the batteries. A telemetry system comprised of voltage dividers, RC low pass filters, and ADC's gather engineering data for transmission to the IHU via I^2C communications.

The design of the Fox-1 MPPT does not require a battery on the output of the PCB for proper operation. In the event of a battery failure where a properly designed circuit will disconnect the battery from the satellite power bus, the MPPT is fully capable of operation. The requirement for this operation however is that no more than maximum power available from the MPPT can be requested from the payload. This means that if the satellite can operate by never drawing more power than the lowest power available from solar panels then indefinite operation without a battery is possible.

Power is obtained from the X and Y axis panels through PCB edge connectors (Samtec *MEC1-105-02-L-D-NP-A*) and through the board-to-board connectors (Samtec *QSH-030-01-L-D-A* and *QTH-030-02-L-D-A*). Besides solar power, signals passing through these PCB edge connectors are the RTD connections (ground referenced) for measurement of each solar panel temperature as well as two antenna deploy and sense channels on the Y panels. The antenna deploy and sense connections are not thoroughly covered in this document, please refer to the schematic. All copper planes have been pulled back from the connector and a maximum of 20 mil traces were used to the connectors themselves to prevent heat loss to space from the MPPT PCB which is necessary for proper operation

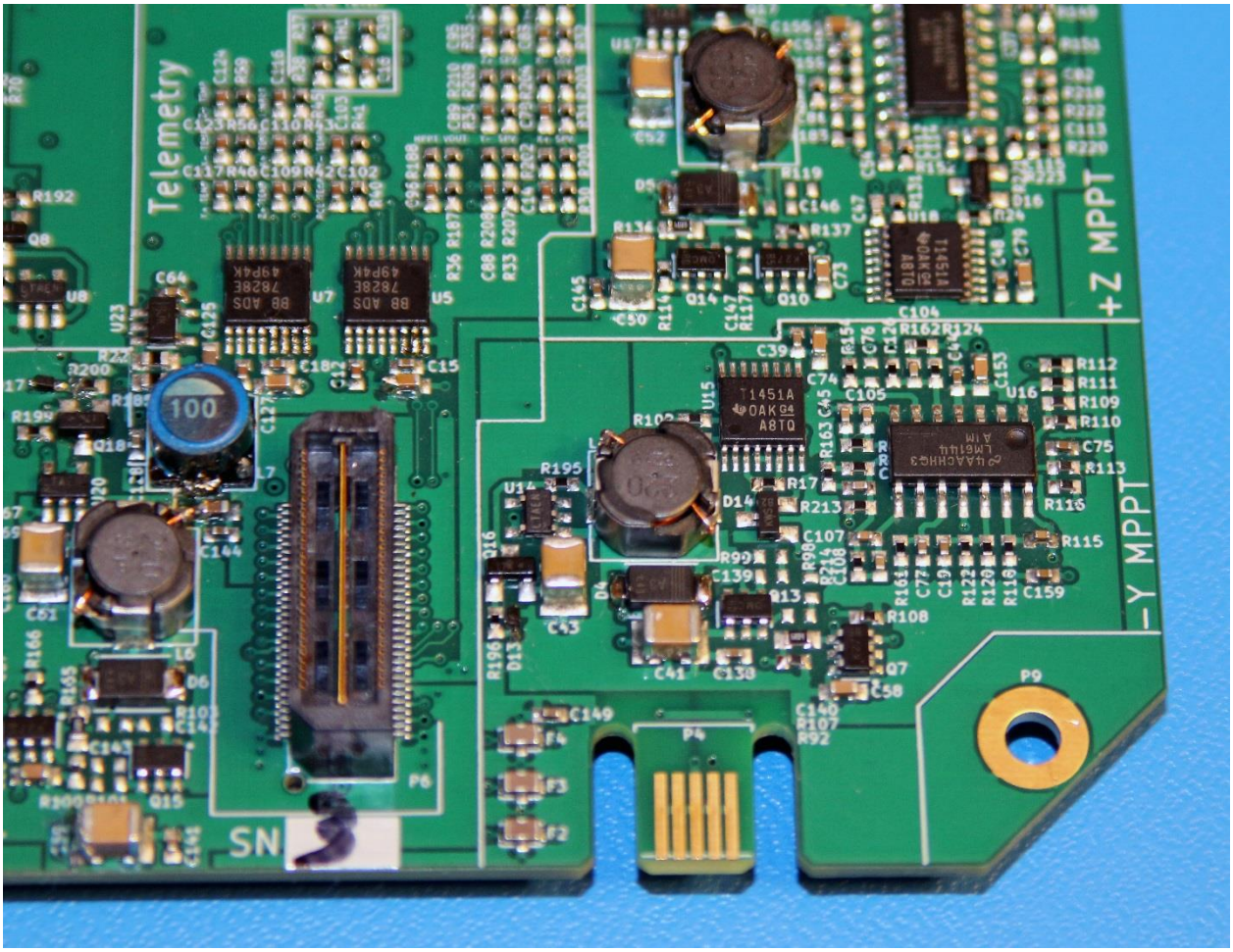


Figure 4: Samtec QTH-030-02-L-D-A board to board connector shown on left side of image, Samtec MEC1-105-02-L-D-NP-A edge connector shown near middle of image with male portion of connector made of PCB material

PCB Design

Each PCB is a four layer board developed in the open source KiCad EDA (Build: 2013-07-07 BZR 4022)-stable on Windows. Gerber files were exported and sent to Advanced Circuits for fabrication. Since Gerbers are very portable file formats, AMSAT has the ability to use almost any manufacturer they choose. All relevant PCB processes have been documented in the "Drawings" Layer of the Gerbers.

PCB Stackup

Top Layer Copper - 1oz (1.4 mils) - TL1451_MPPT_Flight_Rev1_1-F_Cu.gtl	0.062" +/- 10%
2116 Prepreg (4.7 mils)	
2116 Prepreg (5.1 mils)	
Plane GND - 1oz. (1.4 mils) - POS. POLARITY (TL1451_MPPT_Flight_Rev1_1-Inner2_Cu.gbr)	
Core - 40 mils	
Mixed Sig - 1oz. (1.4 mils) - POS. POLARITY (TL1451_MPPT_Flight_Rev1_1-Inner1_Cu.gbr)	
2116 Prepreg (5.1 mils)	
2116 Prepreg (4.7 mils)	
Copper Bottom Layer - 1oz. (1.4 mils) - (TL1451_MPPT_Flight_Rev1_1-B_Cu.gbl)	

Figure 5: Four layer PCB stackup used on the Fox-1 MPPT Rev 1.1 PCB

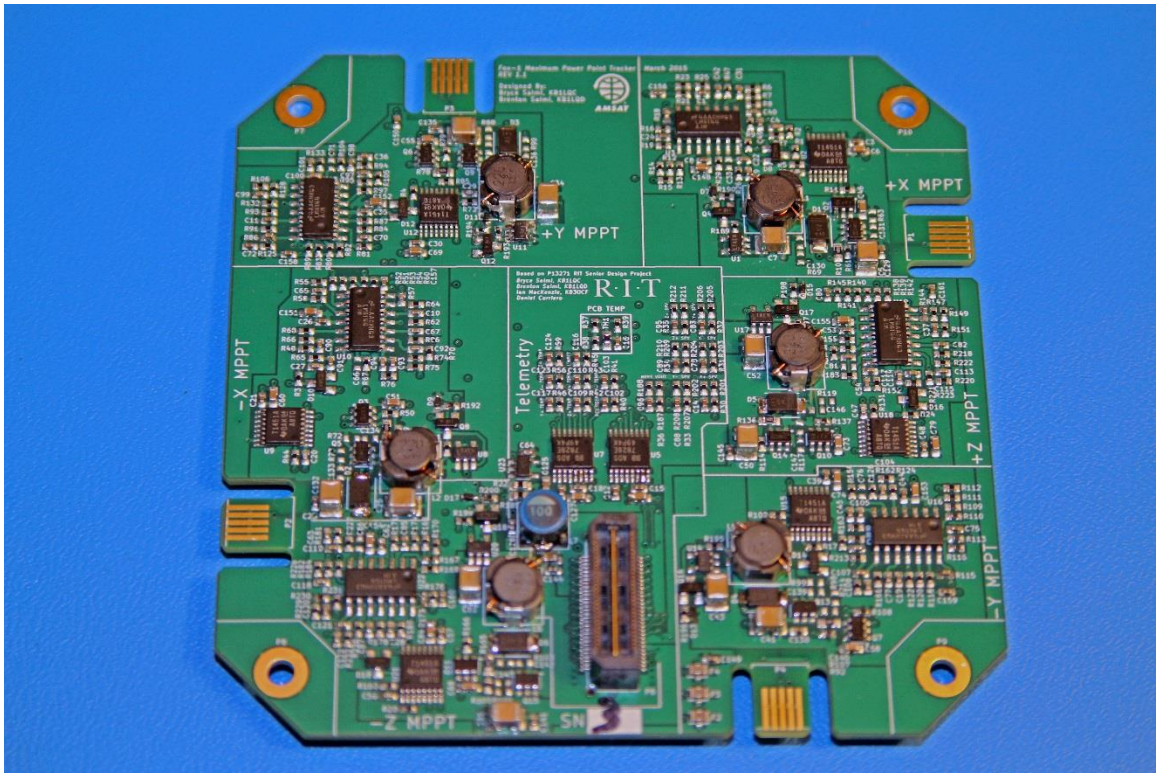


Figure 6: Fox-1 MPPT Rev 1.1 PCB with top layer visible, all components other than stacking connector located on top layer

Maximum Power Point Tracker Design

MPPT Overview

The Fox-1 MPPT is designed as a temperature based set-point constant voltage MPPT and is implemented with analog circuitry to mitigate radiation events associated with holding state. There are two discrete feedback loops implemented in the design, the MPPT feedback loop and an output voltage regulation feedback loop. Both MPPT feedback loop and MPPT as a PCB will be referred to in this document and the context will determine the subject. The output voltage regulation circuitry limits the MPPT channel output voltage to 4.33V prior to the ideal diodes in order to protect the Fox-1 payload and batteries from overvoltage conditions. Using temperature based MPPT allowed power to be maximized without computational resources such as a microcontroller which requires state.

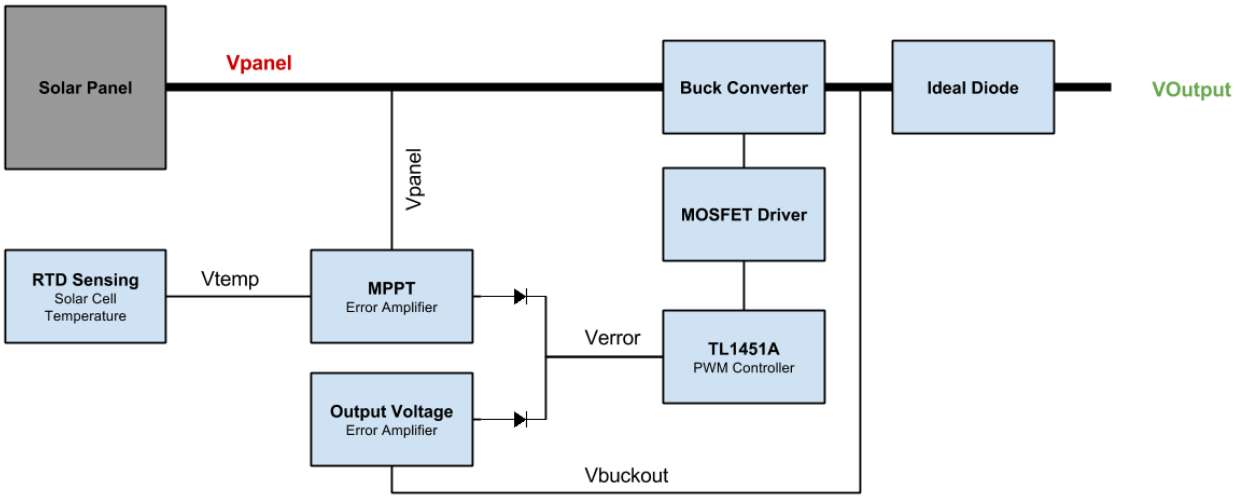


Figure 7: Fox-1 MPPT & voltage regulation feedback block diagram

As shown in Figure 7, there are two feedback loops used to control the TL1451A PWM controller. The internal TL1451A error amplifier is used as a unity gain buffer to directly pass the combined V_{error} signal from the external error amplifiers into the internal comparator used to generate the PWM signal. The inversions from the TL1451A open collector PWM output and PMOS gate create the following V_{error} to duty cycle relationship shown in Table 2.

V_{error} Change	PWM Duty Cycle
Increasing	Decreasing
Decreasing	Increasing

Table 2: Error voltage effect on the PWM duty cycle

Therefore, a simple diode-OR is used to combine both the MPPT error amplifier and output voltage regulation error amplifier signals. *This results in the highest voltage error signal applied to the TL1451A winning control of the buck converter and forcing the lowest duty cycle of the two feedback loops to be implemented*. This is extremely advantageous as shown later in this document.

MPPT Schematics

The latest version of the schematics for the Fox-1 MPPT are located in the AMSAT SVN MPPT folder. Using KiCad to open "*TL1451_MPPT_Flight_Rev1.pro*" one has access to the schematics and PCB files within the KiCad EDA. An important note is that the libraries and footprints used for KiCad live in the SVN Power KiCad folder so those must be checked out too and Kicad may need to be told where they are on your computer to display properly. An annotated PDF version of the schematics is provided with this document.

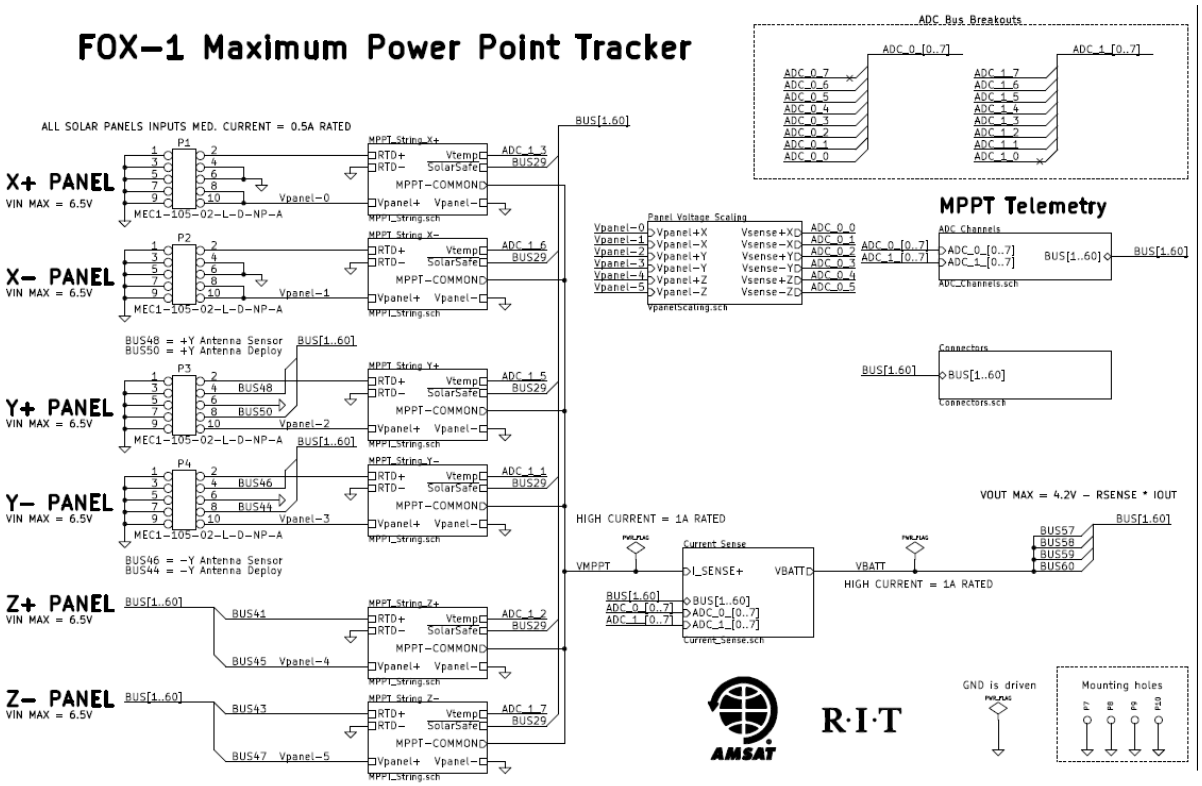


Figure 8: Main schematic page of the Fox-1 MPPT closely resembling the block diagram in Figure 3

The schematics are built up in a hierarchical arrangement as shown in Figure 8 much like block diagrams that contain sub-circuits within individual blocks. This makes understanding signal flows much easier and is very different from how EAGLE presents schematics. The main schematic page looks a lot like the overview block diagram shown in Figure 3. Hierarchical design results in a large number of schematics sheets due to channelization of the design. An annotated schematic included with this document at the 2015 AMSAT Symposium details all unique MPPT PCB circuits without duplication.

Resistive Temperature Detector Circuitry

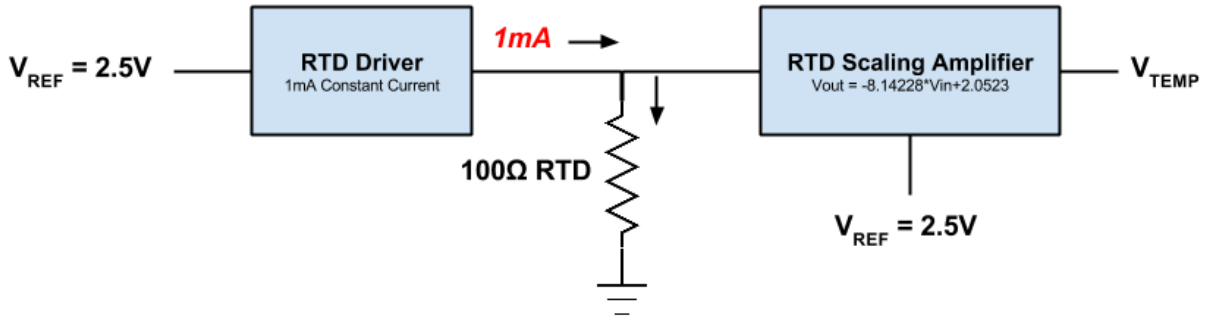


Figure 9: RTD drive and sensing block diagram

The AMSAT MPPT uses resistive temperature detectors, *RTDs*, to accurately measure solar panel temperature which is then used to predict the Maximum Power Point Voltage, *MPPV*. A constant current source forces exactly 1 mA into the RTD leaving only voltage to change with varying resistance as the RTD changes temperature. Both voltage and resistance are directly correlated as governed by Ohms law when using a constant current source. The measured voltage developed across the RTD is conditioned and amplified using a simultaneous equation based op-amp circuit implementing analog mathematics. This produces a voltage mimicking the solar panel voltage at MPPV and can be referenced by the MPPT error amplifier as it compares real panel voltage against this predicted reference voltage. This scaled voltage produced by the amplifier is referred to as V_{temp}. The RTD used for each panel is a PT100 type device, nominally 100Ω at 0°C (PTS080501B100RP100). RTDs are not thermistors, they use a pure metal such as nickel or platinum which have very accurate and predictable changes in resistance over temperature and nearly linear responses over the temperature ranges used.

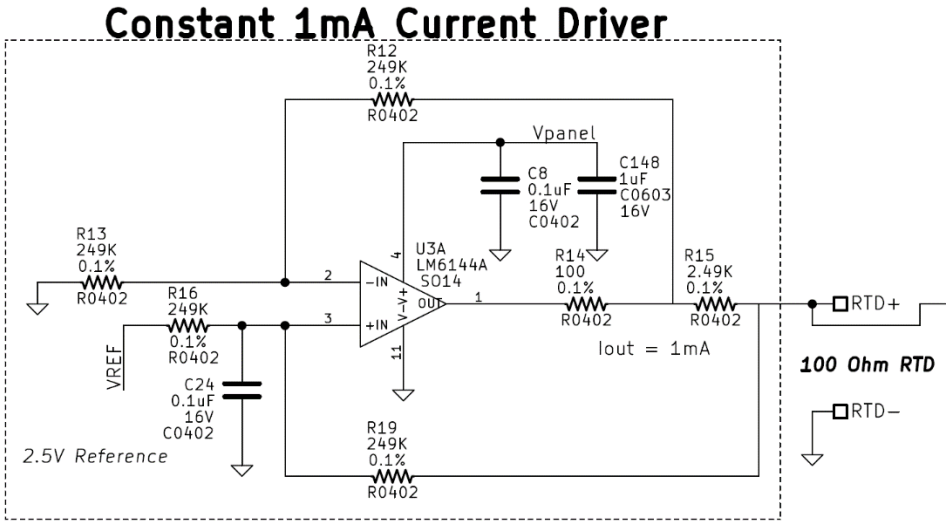


Figure 10: Fox-1 MPPT RTD constant current driver

U3A of Figure 10 is a LM6144A op-amp configured as a constant 1 mA source. Its sole purpose is to force exactly 1 mA of current through the RTD. Figure 11 shows a LTSpice schematic of the 1 mA RTD driver and is used to describe the RTD circuit for the remainder of this description. The following equation determines the output voltage of the op-amp U1:

$$Vout = V_2\left(\frac{R_4}{R_3 + R_4}\right) \times \left(\frac{R_2 + R_1}{R_2}\right) - V_1 \times \frac{R_1}{R_2}$$

Where V_2 is the reference voltage and V_1 is the grounded pad of R_1. However, since R_1, R_2, R_3, and R_4 are all 249KΩ we simplify the equation down to:

$$V_{OUT} = V_2 - V_1 = 2.5\text{V}$$

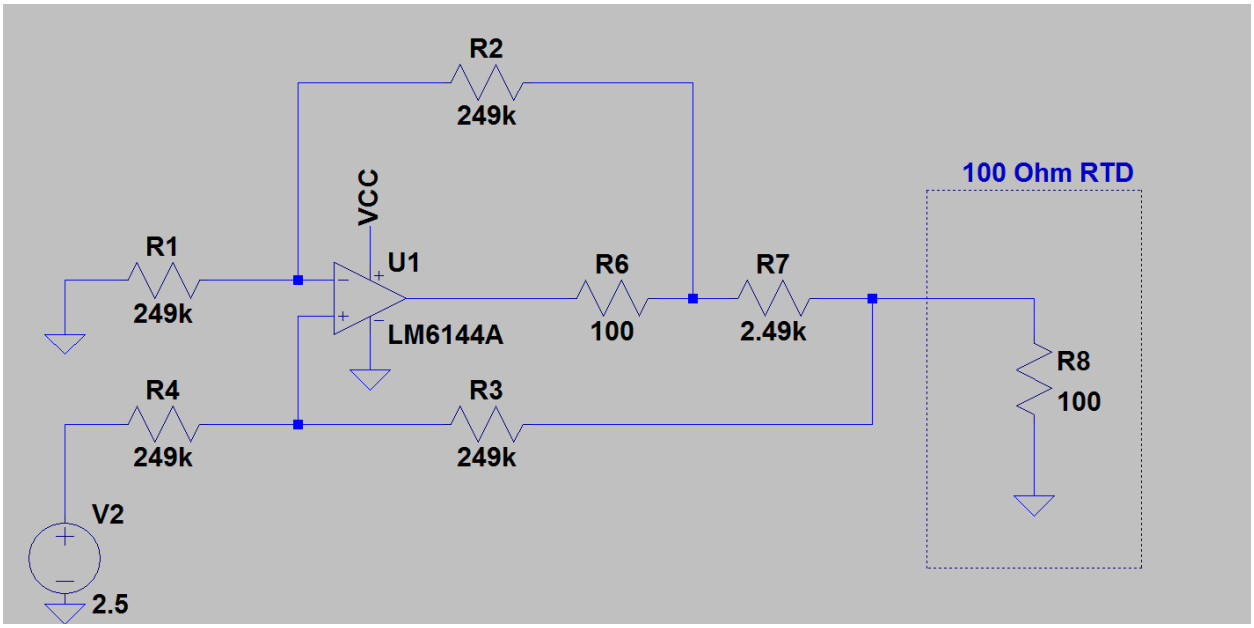


Figure 11: LTSpice 1mA RTD drive simulation schematic, capacitors not simulated.

Knowing we have 2.5V across R7 due to op-amp laws the following relationship for drive current is made.

$$R_7 = \frac{V_2}{I_{Drive}} = \frac{2.5V}{1mA} = 2.5K\Omega$$

With 1 mA of drive current being forced into R8 (a 100Ω RTD) the voltage across it is predictable thanks to Ohms Law. 1 mA of drive current will dissipate about 100uW of power in the RTD and therefore cause minimal internal self-heating of the device and allows for accurate measurements. Table 3 shows several data points along the operating conditions expected in orbit for the solar panels and the respective RTD circuit voltage.

RTD Temperature	Voltage Across RTD
-60°C	0.076V
0°C	0.100V
28°C	0.111V
+60°C	0.124V

Table 3: Expected RTD voltages at 1mA drive current

The voltage across the RTD is very small (between 76mV and 124mV) and exhibits a positive thermal coefficient. This means the voltage increases as the temperature increases. However, the solar cells exhibit a negative temperature coefficient since the MPPT voltage decreases with a temperature increase. An op-amp configured to follow a polynomial equation is used to amplify the measured RTD voltage and flip the RTD voltage thermal coefficient. Essentially the op-amp performs the function $y = -mX + b$ as covered in SLOA076 from Texas Instruments. The flight conditioning circuit implementing analog mathematics is shown in Figure 12. Note that the feedback capacitor C162 is not accounted for in the PCB layout and on MPPT Rev 1.1 was soldered in parallel across the feedback resistor by physically stacking the capacitor onto of R18.

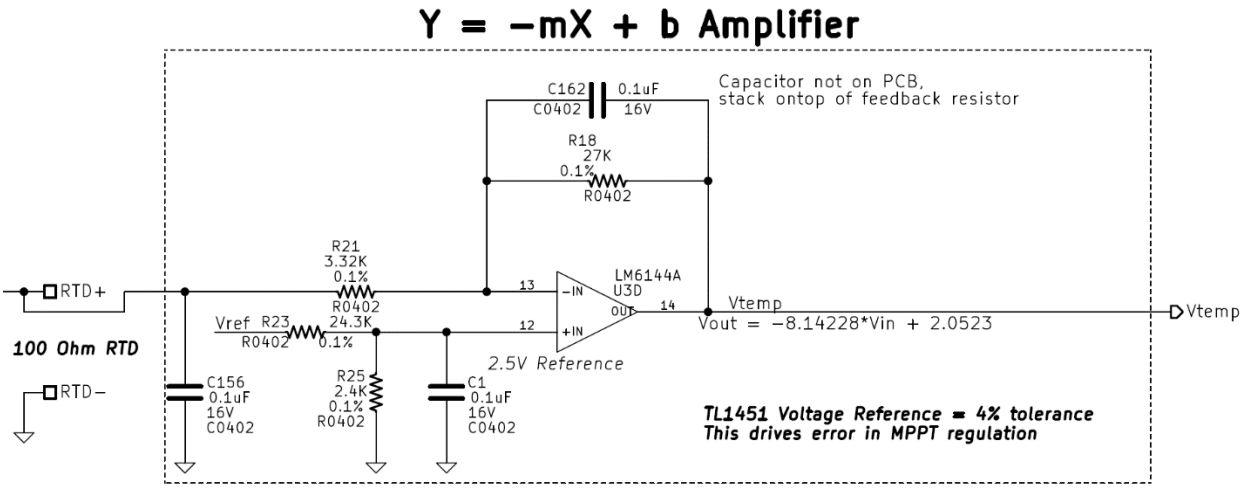


Figure 12: Scaling amplifier implemented on the Fox-1 MPPT panel temperature circuit which mimics solar panel MPPV

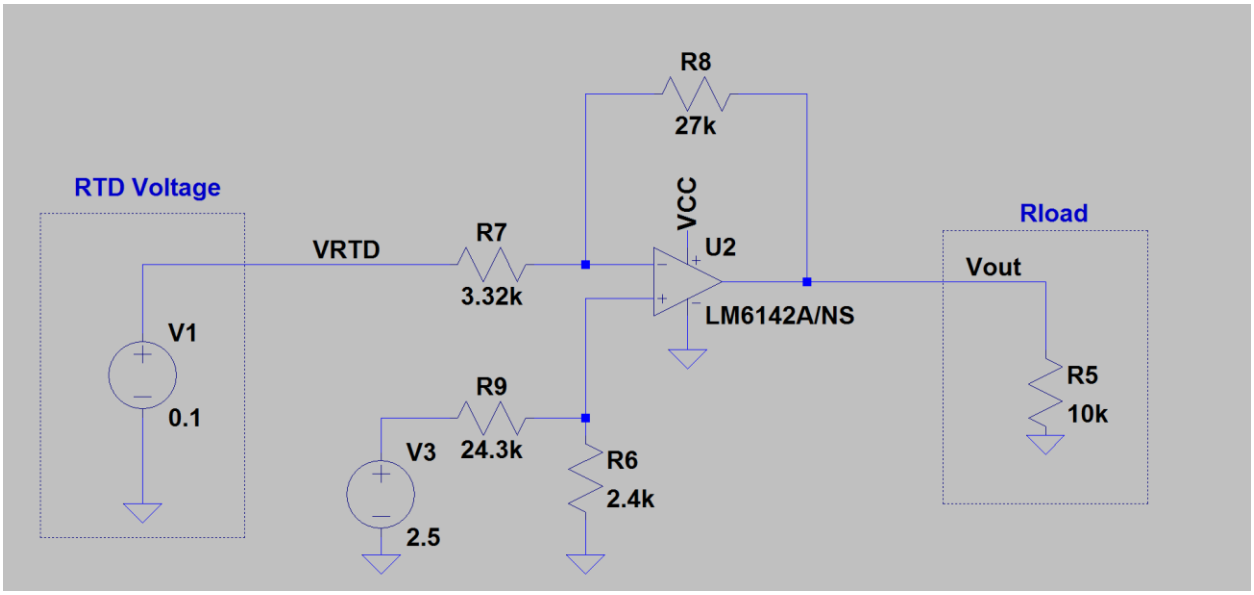


Figure 13: An LTSpice simulation of the RTD scaling amplifier, capacitors not simulated

Figure 13 shows the LTSpice simulation of the RTD conditioning amplifier referenced in the following description. Voltage source V1 represents the RTD voltage being measured and V3 represents the 2.5V reference from the TL1451A. A capacitor is added in the flight circuit across R6 to ground to low pass filter the voltage reference as shown in Figure 12. Another capacitor has been placed across R8 in the flight circuit to reduce the bandwidth of the circuit for stability also shown in Figure 12. A differential amplifier was not used to buffer the RTD since the solar panel PCBs have already been produced and were designed for thermistors which have one of the pins grounded and therefore the RTDs have a grounded pin too, rendering a differential amplifier not effective.

The TL1451A recommended error amplifier input voltage range is 1.05V to 1.45V so the panel voltage has been scaled by 0.245 using voltage dividers before being measured. The RTD predicted panel voltage must mimic this scaled voltage. The voltages in the Fox-1 Solar Panel Calculations in the Appendix show that minimum MPPV is obtained when high temperature panels are tracked at 4.28V and the maximum MPPV is 5.84V when the panels are tracked at low temperatures. This results in a MPPV voltage range of 1.048V to 1.430V present at the MPPT error amplifier during nominal power point tracking. These voltages are used as part of the simultaneous equations solved in SLOA076 and are given in Table 4 which are used to translate RTD measured voltages into the predicted MPPV reference voltage V_{temp}. The predicted voltage is also telemetered to sense panel temperature remotely from Earth via RF telemetry. With some basic mathematics described in the ADC section of this document the panel temperature can be resolved back from this voltage as measured by the ADC.

RTD Temperature	RTD Voltage	Vout Desired
60°C	0.124V	1.048V
-60°C	0.076V	1.430V

Table 4: Voltages used to solve for the scaling amplifiers component values

The values used for the output voltage of the scaling amplifier were chosen based on obtainable resistor values resulting in the following equation relating V_{out} of Figure 13 to RTD voltage:

$$V_{OUT} = -8.14228 \cdot V_{IN} + 2.0523$$

Figure 14 shows the RTD voltage versus scaling amplifier output voltage (predicted MPPV). The amplifier clearly amplifies the voltage as well as flips the temperature coefficient to match the Spectrolab solar cell based panel temperature coefficient.

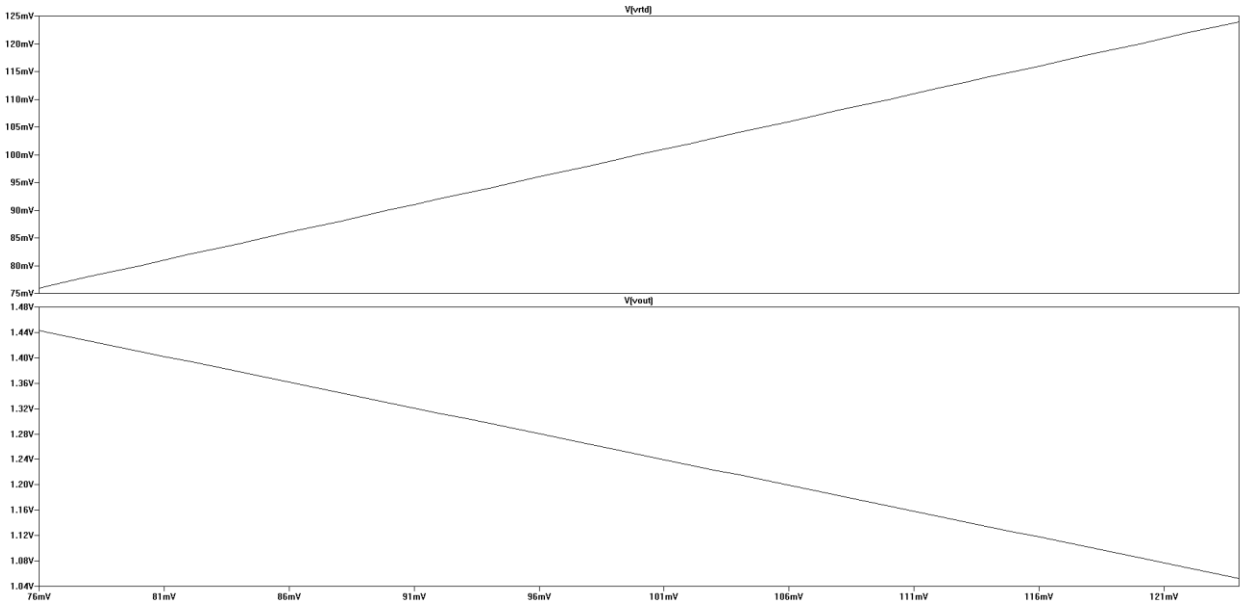


Figure 14: Simulated RTD voltage input to the amplifier and output voltage representing the scaled panel voltage desired. The top graph shows the RTD voltage over the expected operating range while the bottom graph shows the resulting op-amp output voltage for the

Totem Pole MOSFET Driver

The PWM output from the TL1451A is an open collector circuit and cannot provide a low impedance drive signal into the switching MOSFET gate. A low impedance drive signal is necessary to quickly turn the MOSFET on and off. A pull-up resistor, R11 in Figure 15, is connected to the open collector pin of the TL1451A where the PWM signal is output. More information can be found regarding MOSFET drivers in SLUP169 from TI.

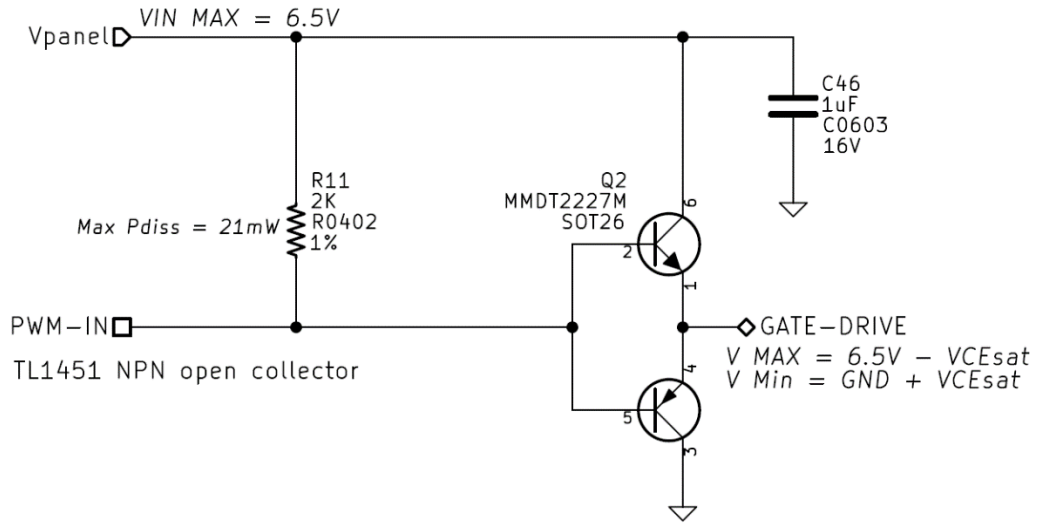


Figure 15: Open collector PWM output and totem pole MOSFET driver

The TL1451A output open collector stage inverts the signal produced by the PWM generator which is then fed into the totem pole driver (Q2 in Figure 15) which is a non-inverting circuit. The totem pole operates by pulling the MOSFET gate close to ground or close to the solar panel voltage, well into saturation or cutoff of the switching MOSFET. When the TL1451A open collector output pulls towards ground this will cause the PNP transistor base of Q2 (pin 5) to be a lower voltage than its emitter (pin 4 assumed at Vpanel) forcing the device into conduction and draining the MOSFET gate (GATE-DRIVE) into ground. Panel voltage from the open collector when it is open circuit will cause the PNP of Q2 to go into cutoff (base is higher voltage than emitter near ground) and then drive the NPN base (pin 2) to a higher voltage than the NPN emitter (pin 1) also near ground. This puts the NPN device into conduction and connects the solar panel voltage to the gate of the MOSFET. The voltage of the MOSFET gate will always be around a V_{BE} below panel voltage or above ground during cutoff and saturation respectively.

Buck Converter

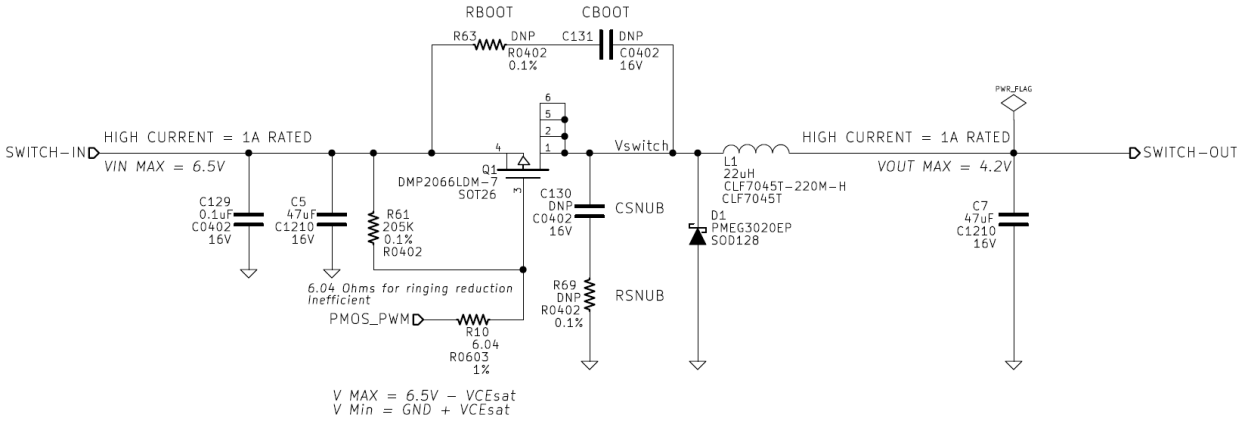


Figure 16: Fox-1 MPPT buck converter switching circuitry

A standard buck converter has been implemented on the Fox-1 MPPT as shown in Figure 16. The output of the totem pole MOSFET driver (GATE-DRIVE) is fed into PMOS_PWM which drives the gate of the P-channel device (PMOS) through a 6.04Ω resistor to dampen ringing. Standard buck converter design techniques were followed (SLVA477) to derive initial component values. The values in Table 5 show the parameters used to initially design the buck converter stage, these are assumptions about operating conditions prior to actually building the converter.

50mA was assumed to be the lowest current the buck converter would see when operating to guarantee continuous conduction mode and 780mA is the amount of current the coldest solar panel operating at MPPT would dump into a fully discharged battery at 3.3V. These are bounds which create a design capable of operating at all times in Fox-1. The design is non-synchronous and uses a catch diode as shown in Figure 16**Error! Reference source not found.**. Increased efficiency could be realized with a synchronous design in the future. Additionally, snubbing and boot RC circuits have been added to allow the control of ringing and edge rise time if necessary from the switching node to ground and the source to drain of the switching MOSFET. In the event that the series resistance to the gate is disconnected, a pullup resistor R61 has been implemented to provide fault tolerance by forcing the MOSFET off in that failure mode.

Parameter	Value	Unit
Minimum Input Voltage	4.284	Volts
Maximum Input Voltage	6.464	Volts
Minimum Output Voltage	3.3	Volts
Maximum Output Voltage	4.33	Volts
Minimum Current	0.050	A
Maximum Current	0.780	A
Assumed Efficiency	90	%
Minimum Duty Cycle	0.5	Ratio
Maximum Duty Cycle	0.98	Ratio

Table 5: Basic buck converter parameters used for the Fox-1 MPPT design

MPPT Feedback

Maximum Power Point Tracking on Fox-1 is achieved by predicting the expected MPPV determined by the measured solar panel temperature using an RTD as previously described. The solar panel voltage, V_{panel}, and predicted MPPV, V_{temp}, are fed into a dedicated MPPT error amplifier built using an LM6144A op-amp as shown in Figure 17.

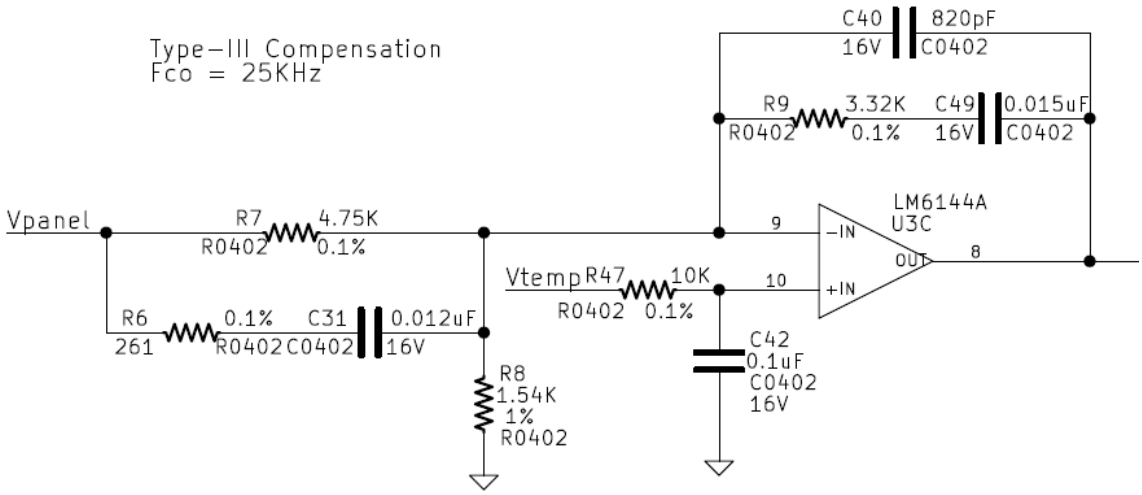


Figure 17: Maximum Power Point Tracking error amplifier

In Figure 17 the solar panel voltage is applied to the voltage divider created by R7 and R8 scaling the panel voltage by 0.245 and driving the inverting input of the op-amp U3C while the RTD measured

V_{Temp} signal is applied to the non-inverting input as the reference voltage for the error amplifier. The op-amp output voltage, V_{error}, is determined by the following equation

$$V_{OUT} = A \cdot (V_{IN+} - V_{IN-}) = A \cdot (V_{Temp} - V_{panel} \cdot 0.245)$$

This means that given a large gain A from U3C, the output of of the error amplifier will decrease towards ground whenever the panel voltage is greater than the predicted V_{Temp}. Likewise, when V_{Panel} is lower than V_{Temp} the output voltage increases towards the VCC voltage rail (panel voltage). The following relationship can be determined:

V_{error} Change	PWM Duty Cycle Change	Panel Voltage	Output Voltage
Increasing	Decreasing	Increasing Voltage	Decreasing Voltage
Decreasing	Increasing	Decreasing Voltage	Increasing Voltage

Table 6: MPPT error amplifier output effect on solar panel and MPPT output voltage

Type-III compensation has been implemented due to the use of ceramic capacitors which exhibit a high frequency resonance with the buck converter and cause a near 180° phase-lag at the crossover frequency: a recipe for switch-mode converter instability. More information about compensating buck converters can be found in SLVA301 from TI and specifically for Type-III in AN-1162 from International Rectifier.

A crossover frequency of 25 KHz was chosen after building the MPPT and performing engineering tests. It was discovered that the TL1451A could not change the output voltage quick enough at its switching frequency when the bandwidth of the error amplifier was set much higher. Therefore, 25KHz was empirically chosen but cannot be drastically increased without instability. This bandwidth is faster than necessary to respond to a spinning Cubesat and provides adequate transient performance.

Output Voltage Regulation Feedback

The purpose of the output voltage regulation error amplifier is to limit the maximum output voltage allowed to 4.33V at all times to protect the payload. A maximum of 4.33V accounts for some voltage drop from the ideal diode resulting in about 4.2V maximum at the battery. When this error amplifier is in control of the buck converter the maximum power of the solar panel is disregarded. This means the operating point is indeterminate but also unnecessary to know since full power is not needed. This occurs when the output voltage is close to 4.33V due to a fully charged battery and enough power from the panels is available to not discharge the batteries. Moving away from the maximum power point causes the extra power to dissipate as heat in the solar cells, radiating into space.

Much like the MPPT feedback error amplifier, the output voltage regulation error amplifier is implemented with a discrete LM6144A op-amp and compensated with a Type-III compensator. A 25KHz crossover frequency of the compensation network was also chosen to play nice with the TL1451A PWM controller. Refer to Figure 18 for the schematic of the voltage regulation error amplifier.

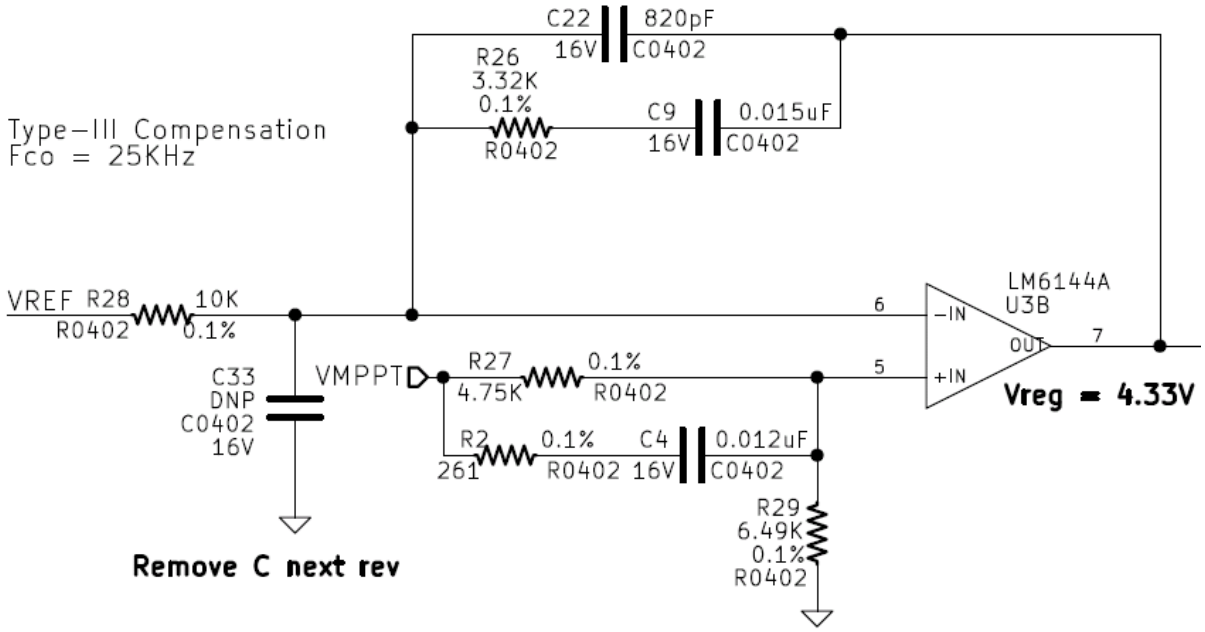


Figure 18: Output voltage regulation error amplifier

The output voltage regulation error amplifier is configured such that the 2.5V voltage reference (from the TL1451A) is applied to the inverting error amplifier input and the buck converter output voltage, V_{Output} (VMPPT), is applied to the non-inverting input. This is a classic voltage regulation error amplifier scheme. Notice that in Figure 18 C33 is DNP'd and a note to remove it is present. During engineering bring-up testing it was determined that C33 caused a low frequency oscillation of the converter and should be removed (along with respective capacitors in other MPPT channels).

The op-amp output voltage is determined by the following equation where A is the open loop gain and the output voltage is scaled to regulate to 4.33V. The resulting duty cycle characteristics can be observed in Table 7. Notice how the effects of the voltage regulation error amplifier signal are exactly the same as the MPPT error signal. The schematic in Figure 18 shows the Type-III compensation modified slightly to invert the output of the LM6144A used as a voltage regulator and match the necessary V_{error} polarity for implementation of the overall circuit characteristics detailed in Table 2.

$$V_{error} = A \cdot (V_{IN+} - V_{IN-}) = A \cdot (0.577 \cdot V_{Output} - V_{ref})$$

Whenever the output voltage V_{Output} is larger than the 2.5V reference, the error amplifier increases its output voltage and PWM duty cycle will trend towards 0% in an effort to reduce V_{Output}. Consequently, whenever V_{Output} is lower than the 2.5V reference, the error amplifier signal will trend towards ground and the duty cycle will trend up towards 100% in an effort to increase the output voltage.

V_{error} Change	PWM Duty Cycle Change	Panel Voltage	Output Voltage
Increasing	Decreasing	Increasing Voltage	Decreasing Voltage
Decreasing	Increasing	Decreasing Voltage	Increasing Voltage

Table 7: Output voltage regulation duty cycle characteristics

TL1451A Pulse-Width Modulation Controller

Converting error signals into Pulse-Width Modulation, *PWM*, signals is the job of the Texas Instruments TL1451A PWM controller shown in Figure 19. This IC provides two synchronized PWM circuits but only one is used on Fox-1, coupling of failure modes of a single TL1451A removing two MPPTs from service was unwarranted. It was also the only PWM controller IC found to operate at the low voltages required and most ASIC MPPTs could not operate above panel voltage of 5V. The TL1451A obtains power directly from the panel it's controlling and therefore it turns on when the panel reaches 3.6V, well above the LM6144A op-amp providing the input error signals which turns on at 1.8V. Thus ensuring valid input signals when powered on. The *PWM* generator uses an RC oscillator comprised of C2 and R5 running the circuit at a nominal 500 KHz. Frequency stability is not critical but thermal stability is highly recommended. The internal error amplifier is setup in a unity-gain configuration and simply buffers the externally generated error signals coming from the MPPT and voltage regulation error amplifiers detailed earlier.

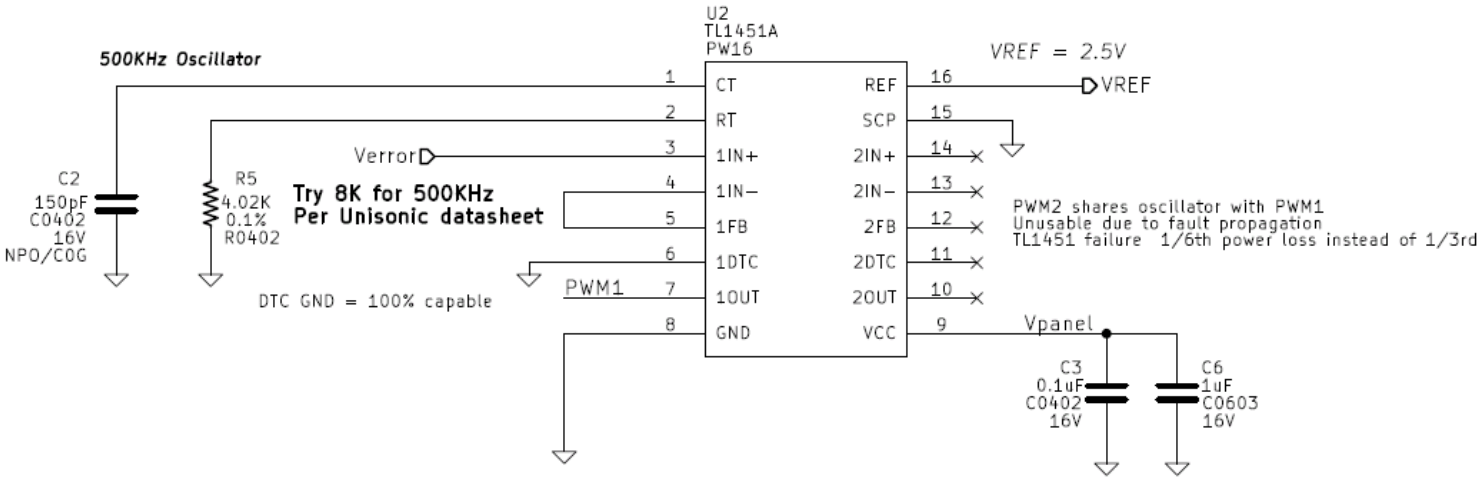


Figure 19: The TL1451 circuitry on Fox-1 used to convert error signals into PWM signals controlling the buck converter

As shown in Figure 20, the TL1451A uses the error signal from Error Amplifier 1 to compare with a triangle wave generated by the oscillator. The dead time control, *DTC*, pin is grounded in Figure 19 as it is disabled. Short-circuit protection, *SCP*, is also grounded and therefore disabled since solar panels effectively limit the short circuit current. The error signal from Error Amplifier 1 (unity gain) is sent into the PWM comparator and then into an AND gate (always passes due to *DTC* pin configuration) which drives an open-collector NPN output transistor. Figure 21 shows the error signal and corresponding waveforms related to the TL1451A.

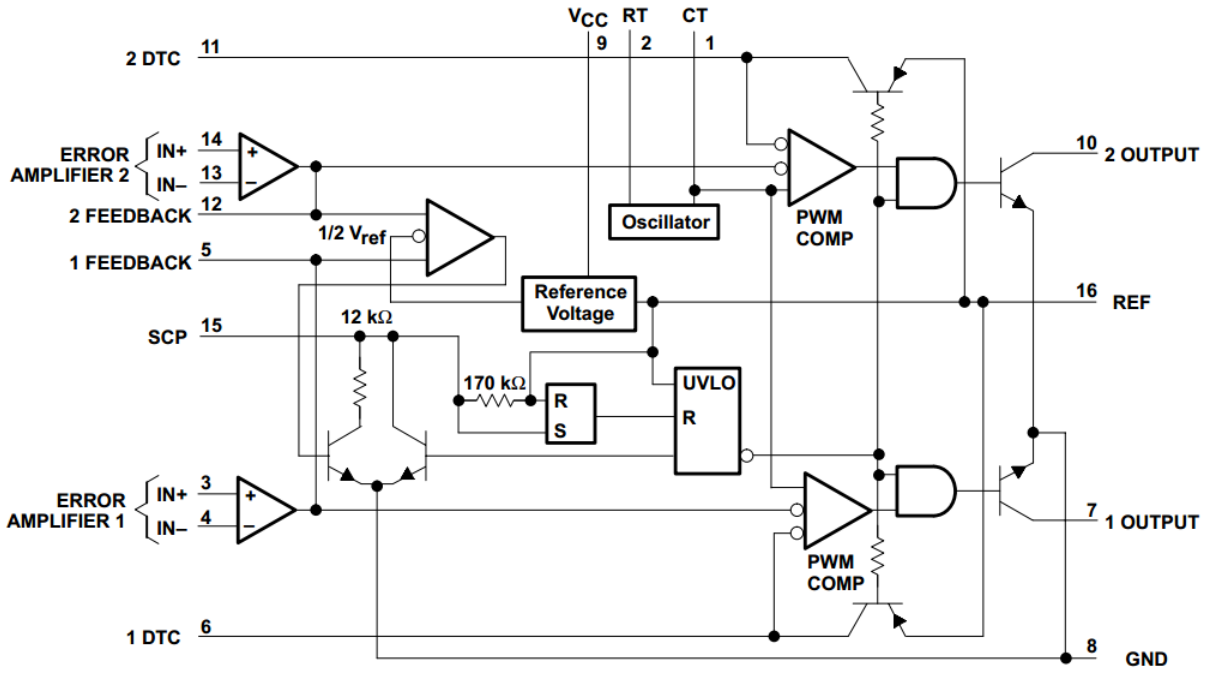


Figure 20: TL1451 block diagram from TI's datasheet SLVS024E

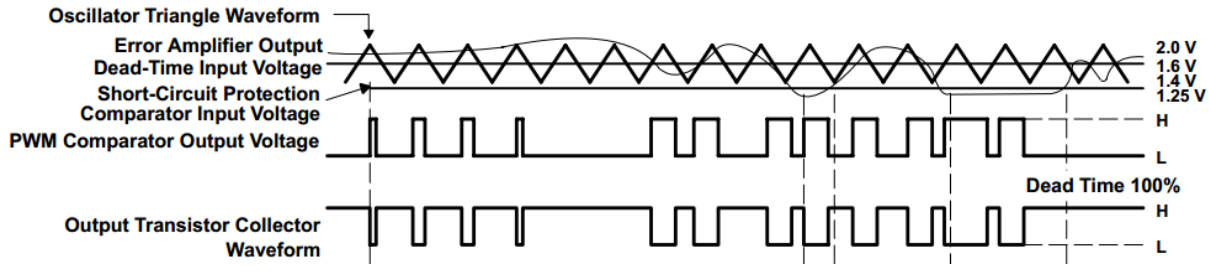


Figure 21: Example error amplifier to PWM open collector output signal path from TI's datasheet SLVS024E

The magic inside the Fox-1 MPPT happens at the output of the MPPT and voltage feedback error amplifiers shown in **Error! Reference source not found.**. Both error signals are combined in a diode-OR configuration with D8, a common cathode Schottky diode array. This combined error signal is sent directly into the TL1451A error amplifier. R1 is a pull down resistor necessary to allow proper operation by discharging the node slightly.

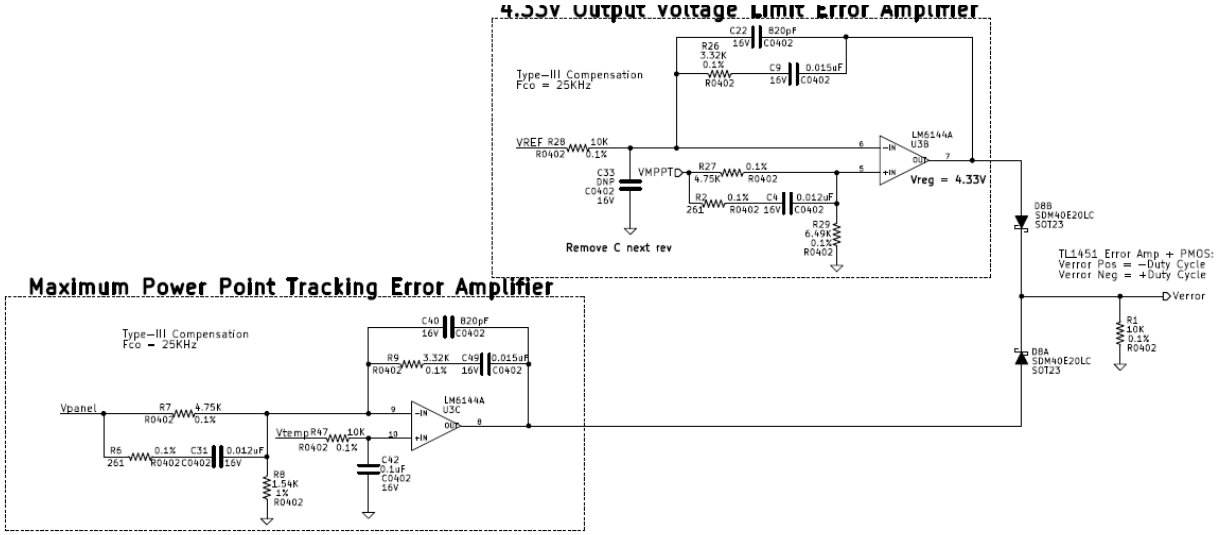


Figure 22: MPPT and output voltage regulation error amplifiers diode-OR connection into TL1451A error amplifier

The resulting effect of the diode-OR circuit combining the error signals in Figure 22 is that the highest voltage error amplifier always wins control of the TL1451A. As noted in Table 2, an increasing error signal demands a lower duty cycle which means this circuit properly interfaces with the PWM controller. Once an error amplifier voltage drops below the other, D8 will reverse bias for that amplifier. The voltage drop across D8 does not matter because the error amplifiers will force up to the solar panel voltage out in an effort to decrease duty cycle (4.28V "lowest" maximum voltage during operation) and automatically compensate for this loss as regulation is maintained.

How MPPT and Voltage Regulation Coexist

It's important to remember the overall interaction of the MPPT and voltage regulation feedback loops must coexist with the input and output power scenarios presented to Fox-1. When the Fox-1 payload is not transmitting and has just finished charging its batteries in full sunlight the panels will be capable of delivering maximum power to the satellite which is no longer using all the power generated. At this point the MPPT feedback loop is in control. Since more power is delivered to the output than needed the output voltage rises and attempts to go above 4.33V. At this point the voltage regulation error amplifier output rises quickly and overtakes the MPPT voltage, reverse biasing D8 for the MPPT error signal, in an effort to reduce the duty cycle and maintain output regulation at 4.33V. This causes the solar panel voltage to rise towards open circuit voltage as less current is being pulled from it, delivering less

power to the payload. Meanwhile, the MPPT feedback loop rails low in an effort to increase the duty cycle, trying to reduce the panel voltage towards MPPV but the output voltage regulation error signal will remain in control since highest error amplifier voltage wins control of the TL1451A. Saturation of the op-amps as they rail towards ground in any case is not really an issue since spacecraft rotation is on the order of a few rotations per minute which allows the op-amps ample time to desaturate.

When Fox-1 enters eclipse with fully charged batteries it will discharge them during the eclipse period. The MPPT is off during this time, however when Fox-1 just comes out of eclipse into sunlight the batteries will be discharged which forces the MPPT output voltage lower than 4.33V. The output voltage of the converter is governed by the battery voltage. The output voltage regulation error amplifier attempts to increase duty cycle to increase the output voltage and increases charging current into the batteries, pulling more current from the solar panels. This continues until the MPPT error amplifier senses that the solar panel voltage has decreased to the predicted MPPV. At this point the voltage regulation error signal has decreased in an effort to increase duty cycle as the panel voltage lowered; delivering more energy to the output in order to maintain 4.33V. However, the MPPT error signal has also started to increase and will eventually be higher than the voltage regulation error signal, forward biasing the D8 for the voltage regulation error signal, causing the maximum power point to be tracked. This remains true until the converter output voltage rises towards 4.33V when the batteries have fully charged and the voltage regulation loop regains control.

The end result is a feedback loop configuration on Fox-1 that only delivers maximum power to the satellite when the satellite demands it; otherwise the MPPT circuitry uses its voltage regulator feedback loop to protect the downstream electronics and moves the solar panels away from MPPT. The MPPT is not expected to properly charge the batteries, which is the job of the battery PCB and circuitry.

Ideal Diode

Each of the six MPPTs has an ideal diode immediately following the buck converter as shown in Figure 23. This provides an efficient power diode-OR function and permits power sharing between MPPTs. Each ideal diode connects to a common output node that is fed into a current sense amplifier before sending power to the Fox-1 payload. The LTC4411 (U1) provides the ideal diode function with only 140mΩ of resistance which equates to 85mW of loss at the maximum output current of 780 mA. The output status pin is not used and the control pin which is active low is pulled up to the solar panel voltage whenever the solar safe circuit is enabled (remove before flight pin inserted); disabling the MPPT from powering Fox-1 at all. This is a launch vehicle safety feature demanded by some launch providers.

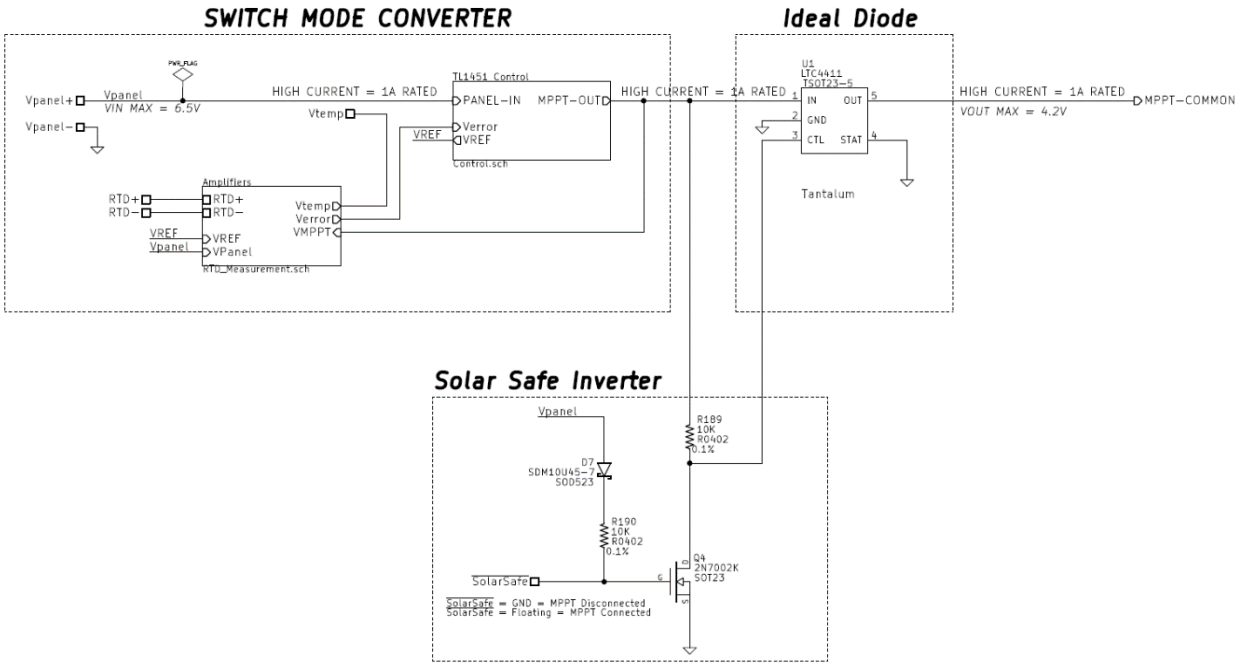


Figure 23: The LTC4411 ideal diode and accompanying solar safe circuitry shown with the MPPT converter circuitry

Solar Safe

In an effort to comply with PPOD and launch vehicle integration needs, the solar safe circuit is used to disconnect all MPPT circuits from the satellite, thus ensuring there is no way the satellite can obtain power while the remove before flight, *RBF*, pin is inserted. The solar safe signal is active low and is essentially a shorting bar to ground. Therefore while the RBF pin is inserted into its hole on Fox-1 the gate of Q4, is pulled to ground and turned off. This forces the ideal diode U1 in **Error! Reference source not found.** to turn off because the control pin is pulled high when the MPPT circuit turns on in sunlight.

Since the gate of Q4 is pulled up through R190 and D7, the shorting RBF pin will conduct through the respective devices to ground. R190 limits the current and D7 is used to prevent a reverse conduction path between each panel. When the RBF pin is the gate of Q4 is pulled up when the solar panel is in sunlight causing Q4 to conduct, pulling the LTC4411 control pin to ground and enabling the flow of current onto the satellite power bus from each MPPT.

Solar Safe is a common node among all six MPPT's of Fox-1. A single piece of Foreign Object Debris, FOD, or other fault pulling this node to ground in flight will completely disable all MPPT's. Disconnecting all MPPTs will cause the satellite to fail once the batteries have been depleted as they can no longer charge.

Telemetry Circuitry

The telemetry circuitry on the Fox-1 MPPT consists of analog voltage, current, and temperature sensing which are digitized by two 12-bit ADS7828 ADC's. Power for all sensing circuitry is obtained from the IHU which is disabled when an IHU failure occurs. Sensor Power is provided from the PCB stack connector and is a regulated 3V. The idea for obtaining power from the IHU is that if/when the IHU gracefully fails it will go into a safe state which disconnects all telemetry power turning off the ADCs and support circuitry for them. This is largely a legacy requirement due to original Fox-1A circuitry designs.

PCB Temperature Thermistor Scaling

PCB temperature is measured by a thermistor powered by sensor power (3V) and attached to a linearizing circuit. The thermistor, TH1, is shown in Figure 24 and is linearize by R37, R38, and R39 while stabilized by C16. The resulting voltage is connected to Channel 0 of ADC 2. The linearizing circuit is based on the output from the Vishay Resistor/Thermistor Netsim Tool.

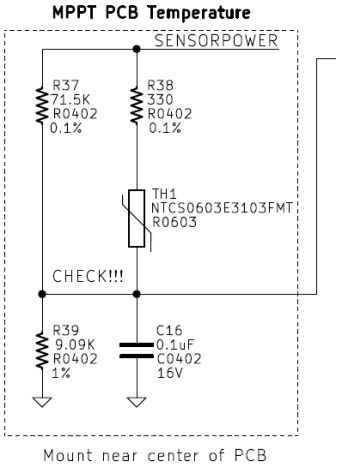


Figure 24: NTC thermistor linearizing circuit used to measure PCB temperature

Output Current Sense

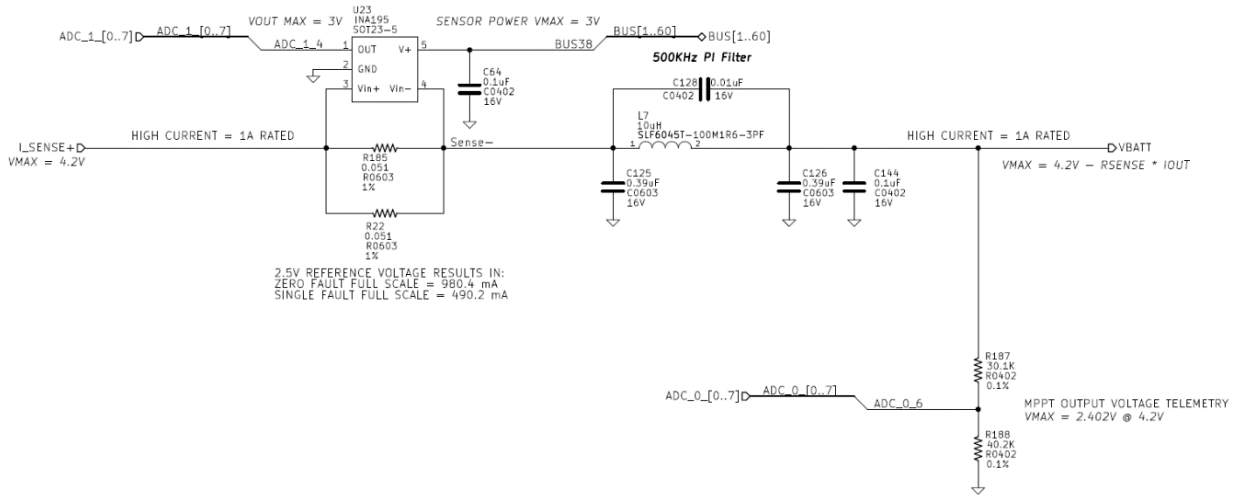


Figure 25: All MPPTs combine and feed through a current sense circuit for telemetry purposes

The common I_SENSE+ node is a combination of all six MPPT outputs following their respective ideal diodes. The INA195 from Texas Instruments is a 100V/V current shunt monitor measuring the voltage across a parallel combination of R22 and R185 shown in Figure 25. The shunt resistors are dual redundant to protect against a bad solder or vibration damage on one resistor causing complete current path loss and consequently mission failure.

In a parallel configuration the current shunt is nominally 0.0255Ω and will drop 19.9mV at the maximum output current of 780mA which is amplified by the INA195 to 1.989V. This dissipates about 15.5mW of power between both resistors at maximum current. In a fault case of either shunt resistor, a single 0.051Ω resistor will dissipate 31mW and the INA195 will attempt to amplify the signal up to 3.9V at maximum current but the output will be saturated at 3V from sensor power provided by the IHU. Table 8 shows the nominal and fault operation characteristics of the amplifier. Since the maximum output current from a single MPPT is 780mA, a failure of R22 or R185 will be observable as 980 mA whenever the current is expected to go over 490mA due to ground telemetry scaling coefficients. This should be obvious when compared to nominal operation data as full scale operation should not be common.

Shunt Resistance	ADC Full Scale Current	Mode
0.0255Ω	980mA	Nominal
0.051Ω	490mA	Fault

Table 8: Current shunt and amplifier values in nominal and fault modes of R22 and R185

Following the current sense amplifier is a capacitive input PI filter used to provide a low pass filter for MPPT voltage powering Fox-1. The parallel capacitor across L7 provides a deep null at the switching frequency.

Voltage Scaling Circuitry

The voltage dividers shown in Figure 26 scale all panel voltages by 0.428. This scaled voltage is then input into the low pass filters of the ADCs detailed next.

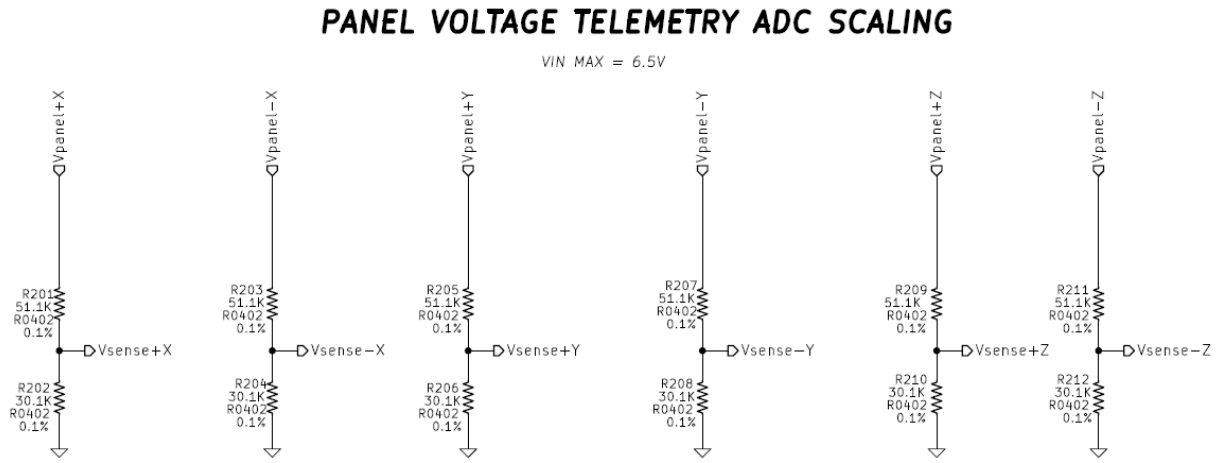


Figure 26: Voltage dividers used to scale solar panel voltages

Analog-to-Digital Converters

The ADS7828 ADCs communicate to the IHU via the I^2C protocol over the PCB stack connectors. These 12-bit ADCs are powered from 3V sensor power provided by the Fox-1 IHU card. The reasoning for this power configuration is to ensure that the ADC's are only turned ON/OFF when the microcontroller is operating correctly. Internal 2.5V references are used by the ADS7828 ADCs as commanded by the Fox-1 IHU via I^2C. This means each bit represents 610.4 uV on the ADC input, providing adequate resolution. Figure 27 and Figure 28 show the ADCs as implemented on the Fox-1 MPPT PCB.

16 Hz low pass filters are used to filter out high frequency content as telemetry is only sampled once every 15 seconds. This was deemed a suitable and realistic filter value. On-board IHU oversampling could be used to prevent aliasing but most signals of interest are so low frequency that avoiding aliasing is not a huge concern and that topic is outside the scope of this document. The filters also provide current limiting functionality for ADC protection. The series 10KΩ resistors limit current into the ADC to no more than about 320uA per channel when the ADC is on and about 650uA per channel when the ADC is off. It is important to remember that this only occurs during fault cases if signal conditioning circuits short panel voltage to the low pass filters. The limiting resistance works in conjunction with internal protection diodes inside the ADS7828 which conduct into the sensor power rail and ground.

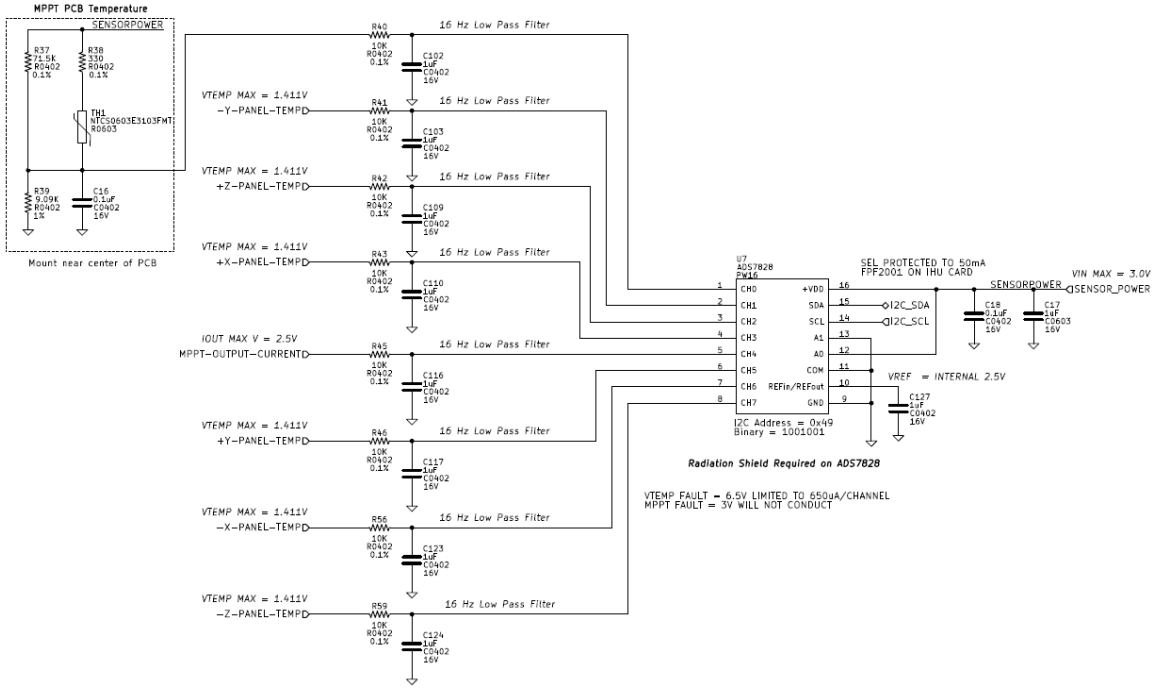


Figure 27: ADC 1 used to obtain PCB temperature, solar panel temperature, and output current telemetry.

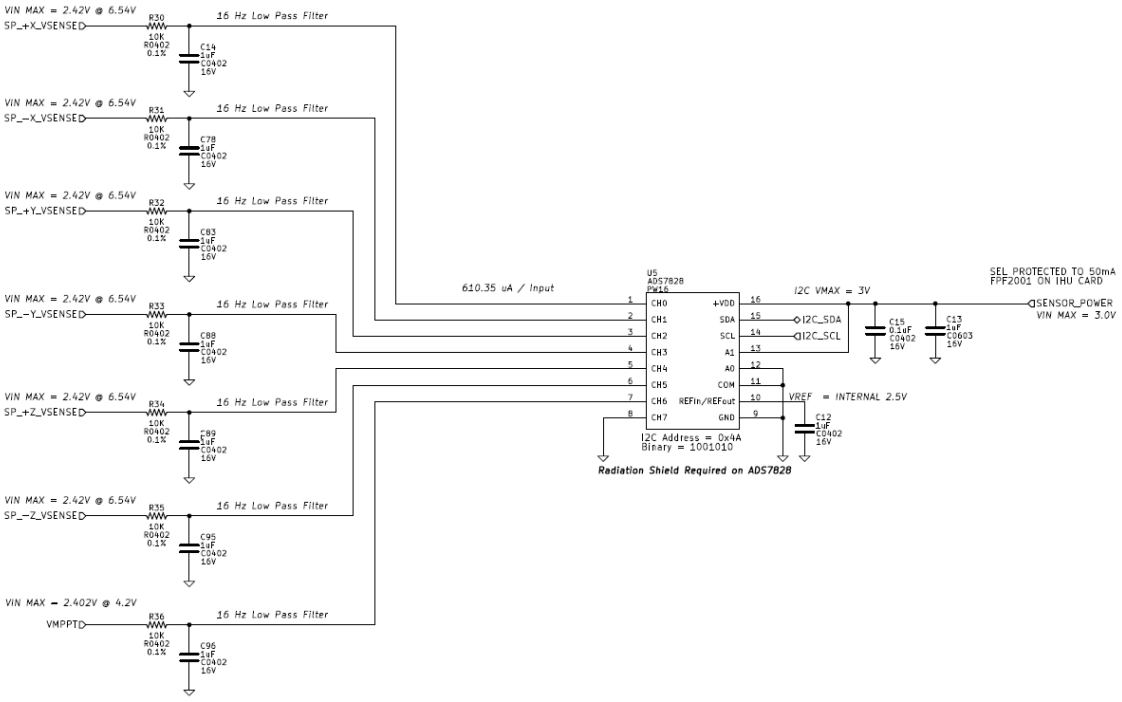


Figure 28: ADC 2 used to obtain solar panel and MPPT output voltage telemetry.

The I²C communications defined in the AMSAT PSU to IHU ICD states that the IHU will be the I²C master while the MPPT PCB ADCs will be slaves and that communications are established at 10 KHz. For more I²C details please refer to the AMSAT PSU to IHU ICD.

ADC 1 (I²C Address = 0x49)		
ADC Channel	**Telemetry Signal**	**Bit Scaling (Y = mX + b)**
0	PCB Temperature	Same as LDO PCB on Fox-1A
1	-Y Solar Panel RTD Resistance	m = -0.074961, b = 252.1
2	+Z Solar Panel RTD Resistance	m = -0.074961, b = 252.1
3	+X Solar Panel RTD Resistance	m = -0.074961, b = 252.1
4	MPPT Output Current	m = 2.3935E-4, b = 0
5	+Y Solar Panel RTD Resistance	m = -0.074961, b = 252.1
6	-X Solar Panel RTD Resistance	m = -0.074961, b = 252.1
7	-Z Solar Panel RTD Resistance	m = -0.074961, b = 252.1

Table 9: ADC 1 telemetry signals and scaling factors

ADC 2 (I²C Address = 0x4A)		
ADC Channel	**Telemetry Signal**	**Bit Scaling (Y = mX + b)**
0	+X Solar Panel Voltage	m = 0.001647, b = 0
1	-X Solar Panel Voltage	m = 0.001647, b = 0
2	+Y Solar Panel Voltage	m = 0.001647, b = 0
3	-Y Solar Panel Voltage	m = 0.001647, b = 0
4	+Z Solar Panel Voltage	m = 0.001647, b = 0
5	-Z Solar Panel Voltage	m = 0.001647, b = 0
6	MPPT Output Voltage	m = 0.001647, b = 0
7	UNUSED (Grounded)	NONE

Table 10: ADC 2 telemetry signals and scaling factors

RTD Panel Temperature Scaling

Solar panel temperature is measured by a RTD on each solar panel and analog mathematics performed by op-amps condition this voltage to mimic the solar panel MPPV. These mathematics can be reversed to directly calculate RTD resistance. Table 9 contains the RTD scaling values which compute the resistance in Ohms from the bit value of the ADC. The ADC scaling values implement a simplified form of the equation below

$$R_{RTD}(\Omega) = \left[\frac{ADC\ Bits\ \times \left(\frac{2.5V}{4096}\right) - 2.0523}{-8.14228}\right] \times \left(\frac{1}{0.001A}\right)$$

All values used to determine the RTD scaling values were rounded to the 6th decimal place as this equation is pure mathematics and considered ideal. The TL1451A reference voltage has a pretty loose initial tolerance and essentially must be calibrated out to make the temperature sensing via ADCs very accurate. This is an MPPT specific process that results in six calibration values for each satellite and is outside the scope of this document. A cubic fit is used to convert RTD resistance into degrees Celsius. The basic formula for a cubic fit of a PT100 RTD is:

$$Temperature\ (C) = -247.29 + 2.3992 \times R + 0.00063962 \times R^2 + 1.0241E - 6\ \times R^3$$

Test Results

Testing was performed using a combination of digital multimeters, an active load, an Arduino™ with a current sense circuit and I²C communications, and a digital oscilloscope. Various other tools were used but are not relevant to this document. Circuit operation as well as performance data will be showcased in an annotated form.

MPPT Operation

Operation of the MPPT is clearly shown in Figure 29. A 2.5 Farad super capacitor was used as a battery simulator to hold up the output voltage and allow plotting of a nice graph. As shown, the capacitor started fully charged at about 4.25V and was constant current discharged down to 3.3V where the load was removed. More power was demanded from the MPPT PCB than the maximum power the solar panel simulators could provide causing a slow but linear decrease in panel voltage. The super capacitor was then allowed to charge back up. It's obvious to see that the panel voltage was near the open circuit voltage when the capacitor was fully charged but as the capacitor voltage decreased the MPPT feedback loop kicked in and forced the panel down to about 4.8V to operate at maximum power (+-5% error at 0C). When the capacitor charged back up the MPPT feedback loop lost control and the voltage regulation feedback loop took over limiting capacitor voltage but allowing panel voltage to rise.

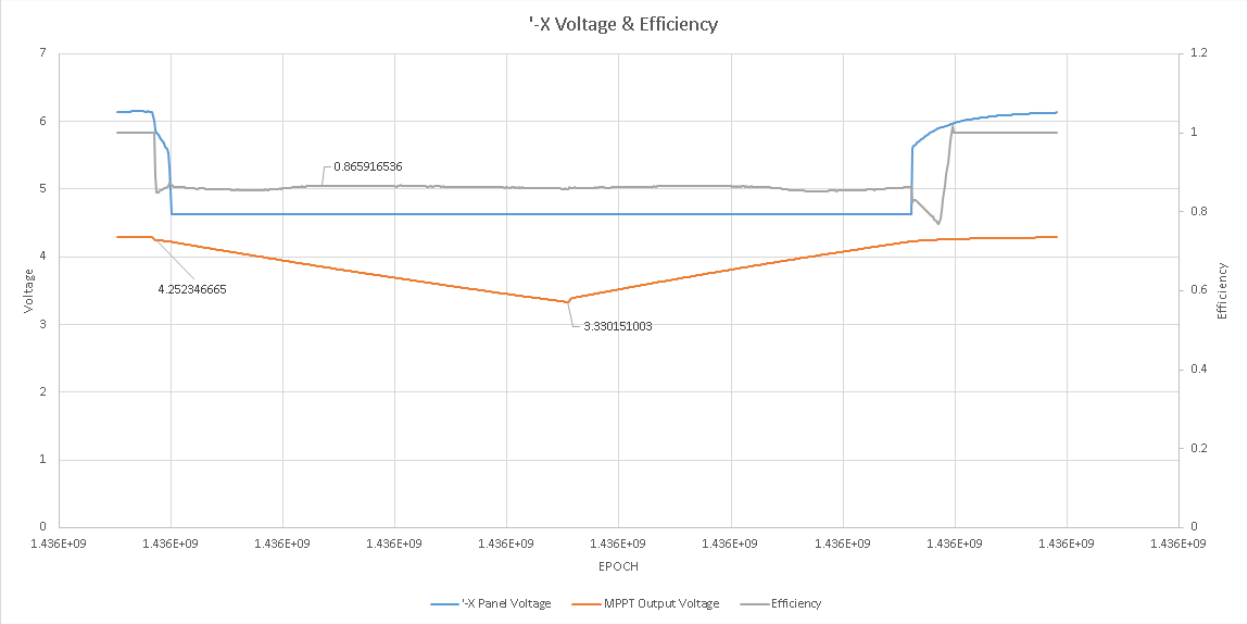


Figure 29: -X Panel operation as obtained by ADC telemetry through an Arduino™ test setup and an external current sense to computer input and output power for efficiency calculations

Figure 30 nicely plots the input and output power of the MPPT and the resulting efficiency. Numbers are only valid during the time the test is occurring. The output power has a linear decreasing slope which is caused by series resistance from the buck converter, ideal diode, and current sense circuits. Ohm's law! The power reaching the MPPT output drops as I^2R losses increase when output current increases as the capacitor voltage decreased and conservation of power must be maintained.

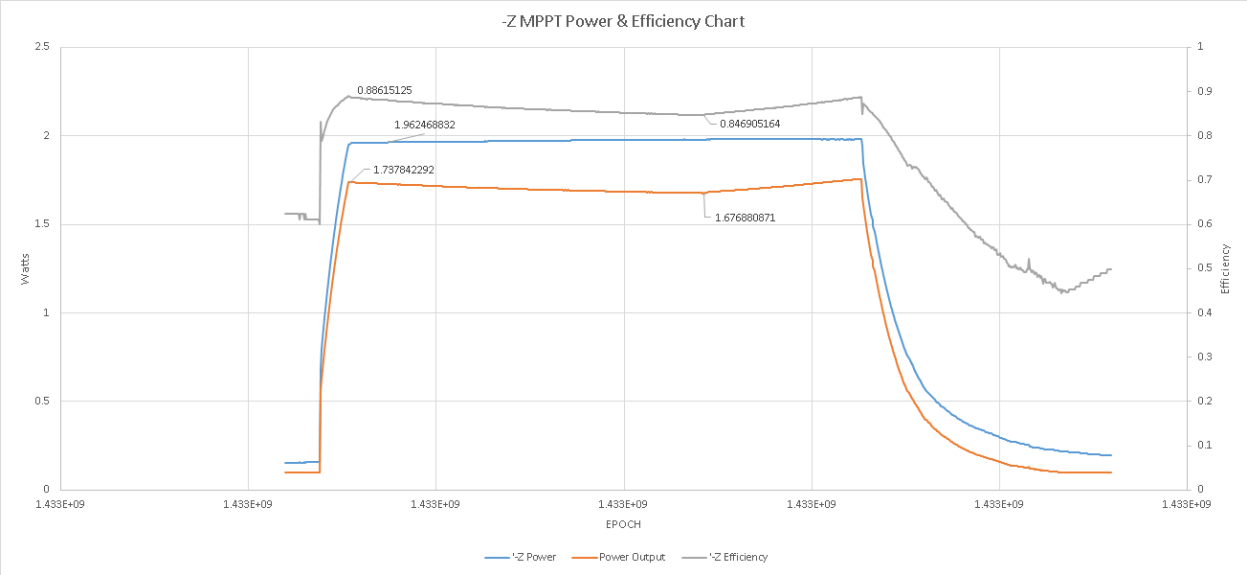


Figure 30: -Z panel operation showing solar panel power output, MPPT output power, and resulting efficiency over a super capacitor discharge test

Oscilloscope Captures

To showcase some of the MPPT operations Figure 31 is an oscilloscope capture of an MPPT load test. Channel 1 (top) is the simulated solar panel voltage, Channel 2 (middle) is the output voltage, and Channel 3 (bottom) is the switching node of the buck converter. A 50mA constant current load was the steady state operation condition the test started in. This means the MPPT was actually in voltage regulation mode to begin the test. A 1A constant current transient was immediately placed onto the output of the MPPT (super capacitor) as a large load causing the capacitor voltage to sag slightly as shown in channel 2 when the test occurred about 100us from the left edge of the screen. Please note this test is extremely unforgiving and unrealistic in orbit but a great example non-the-less.

Transitioning from voltage regulation mode into MPPT mode, the solar panel voltage dipped a bit below the maximum power point and then rose back up to maintain MPPT. Channel 3 clearly shows the duty cycle of the buck converter changing as the feedback loops maintain regulation. The switching node duty cycle is the important observation and absolute voltage of the switching node will track with the panel voltage as shown. Complete tradeoff of voltage regulation to MPPT regulation is observed in this oscilloscope capture. This event occurred in about 1ms from beginning to end which is more than sufficient for on-orbit performance since spacecraft rotation is much slower.

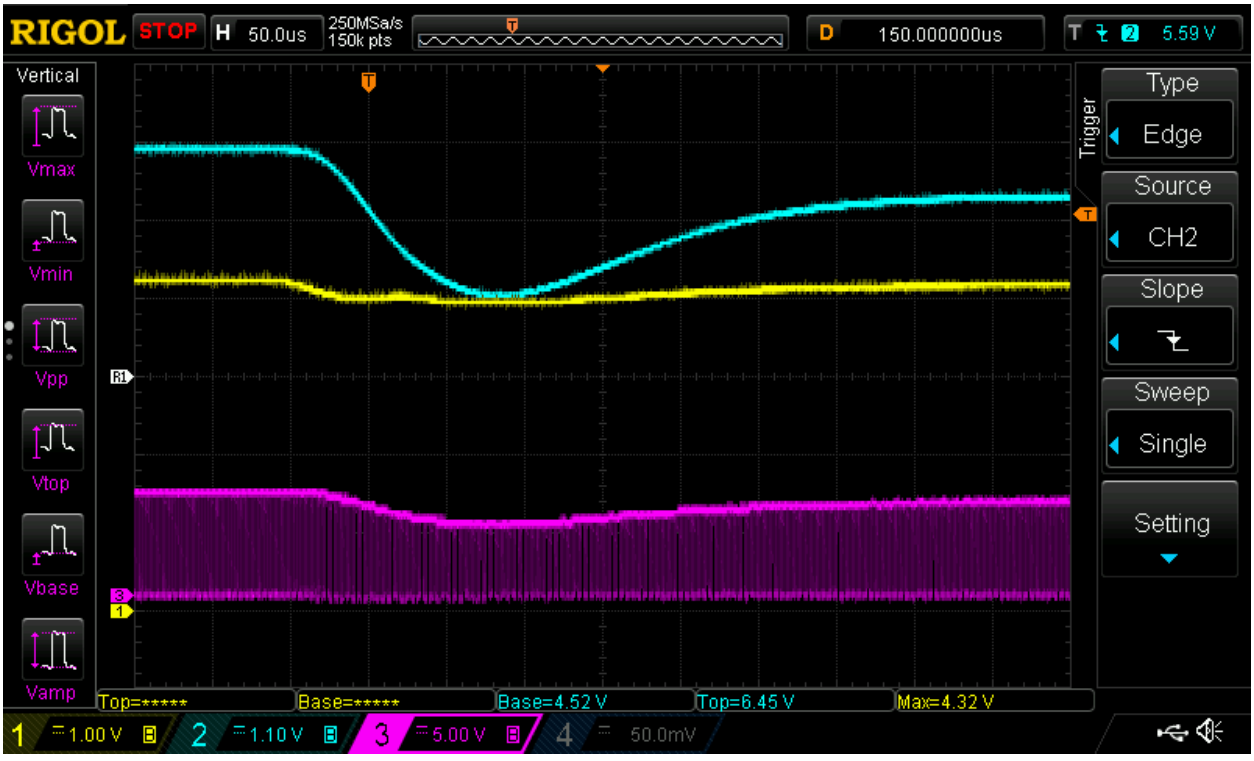


Figure 31: MPPT Operating with a charged super capacitor simulating a battery experiencing a load transient. Load was intense 50mA to 1A transient.

Appendix

Fox-1 Solar Panel Calculations

Fox-1 Solar Panel

PV Temp (C)	V_{OC} (V)	V_{MPP} (V)	I_{MPP} (A)	P_{MPP} (W)
-60	6.464	5.844	0.440	2.571
-55	6.399	5.779	0.440	2.543
-50	6.334	5.714	0.440	2.514
-45	6.269	5.649	0.440	2.486
-40	6.204	5.584	0.440	2.457
-35	6.139	5.519	0.440	2.428
-30	6.074	5.454	0.440	2.400
-25	6.009	5.389	0.440	2.371
-20	5.944	5.324	0.440	2.343
-15	5.879	5.259	0.440	2.314
-10	5.814	5.194	0.440	2.286
-5	5.749	5.129	0.440	2.257
0	5.684	5.064	0.440	2.228
5	5.619	4.999	0.440	2.200
10	5.554	4.934	0.440	2.171
15	5.489	4.869	0.440	2.143
20	5.424	4.804	0.440	2.114
25	5.359	4.739	0.440	2.086
28	5.320	4.700	0.440	2.068
30	5.294	4.674	0.440	2.057
35	5.229	4.609	0.440	2.028
40	5.164	4.544	0.440	2.000
45	5.099	4.479	0.440	1.971
50	5.034	4.414	0.440	1.943
55	4.969	4.349	0.440	1.914
60	4.904	4.284	0.440	1.886

Table 11: Estimated operating parameters of the Fox-1 solar panel using two Spectrolab UTJ cells in series

Maximum Power Point Tracking Theory

Solar Panels convert the Sun's energy into electrical power for use by Fox-1. Due to the high impedance nature of solar cells, the payload can drastically affect the amount of power extracted from the cells by changing the voltage of panels with current draw from them. There is a specific voltage at which the maximum amount of power may be extracted which is called the Maximum Power Point Voltage, *MPPV*. This voltage varies with temperature and solar irradiance. An MPPT follows the maximum power point as it moves due to environmental disturbances.

The standard view of solar cell performance is by that of a current-voltage curve or IV curve as shown in Figure 32 from the Spectrolab UTJ solar cells used on Fox-1. To understand how to obtain information from the chart start with the two extremes. An open-circuit conducts no current and will operate the solar cell at the maximum voltage of about 2.66V on the bottom right of the IV curve. As current drawn from the solar cell is increased by the payload, the operating point of the solar cell moves from right to left along the plotted line. Under a short circuit condition the solar cell shows zero volts of potential and deliver about 17.05 mA/cm^2 of solar cell area to the load.

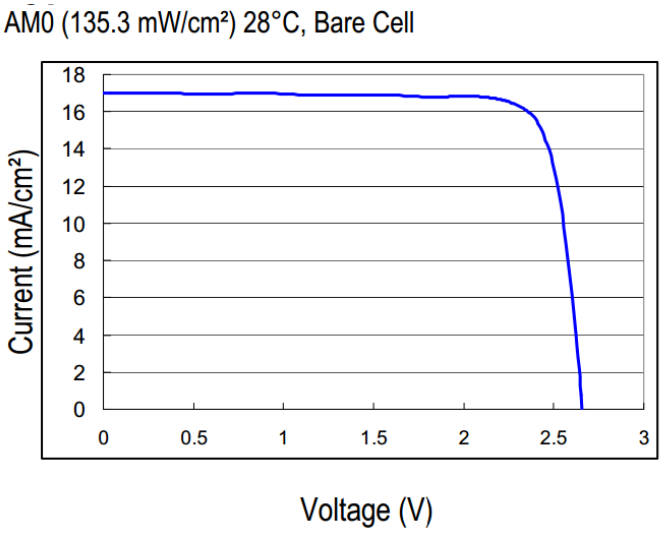


Figure 32: Spectrolab UTJ 28.3% efficiency solar cell IV curve

These two extremes both produce zero power in the ideal world.

$$Power = 2.66\,V \times 0\,A = 0\,Watts\ (open\ circuit)$$
$$Power = 0\,V \times 16.3\,{}^{mA}/_{cm^2} = 0\,Watts\ (short\ circuit)$$

The "knee" of the IV curve shown at about 2.35V on the x-axis is the maximum power point where the most energy can be extracted from the solar cell and delivered to the payload. Figure 33 shows example power curves and IV curves are as the values vary with temperature and irradiance of the solar cells. Notice how temperature is a huge contributor to changing the maximum power point.

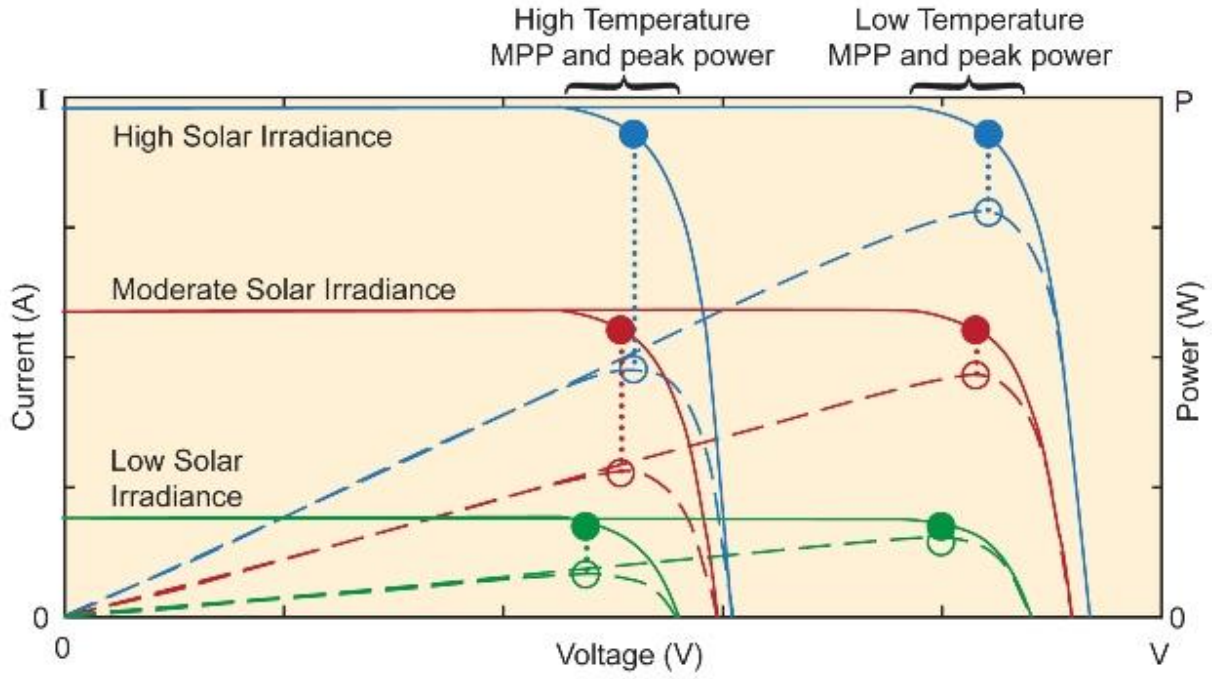
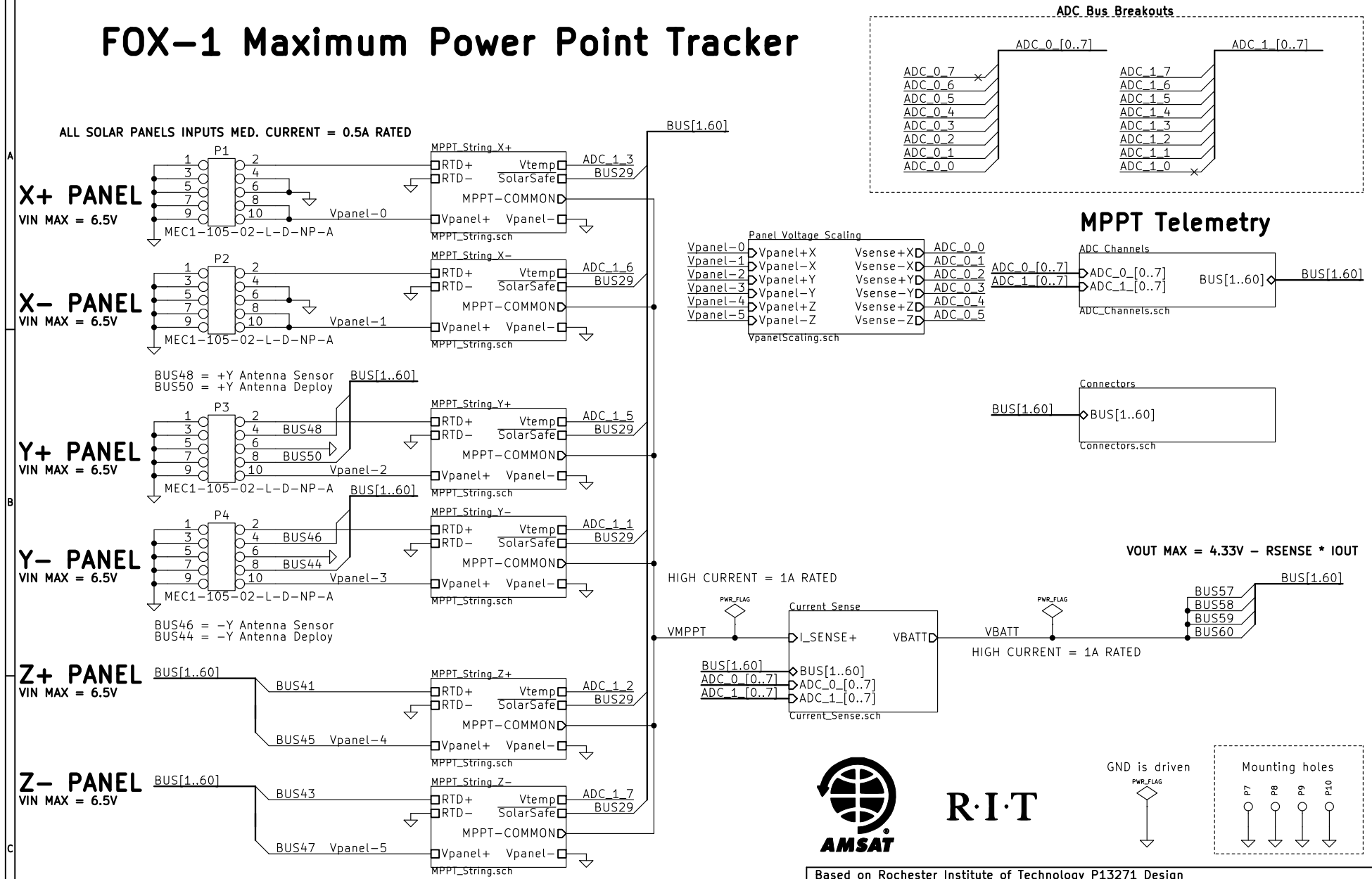


Figure 33: Solar panel MPPT versus temperature and irradiance changes. Image used from http://www.electronicproducts.com

A maximum Power Point Tracker is an intermediate circuit between the solar panels and the battery/satellite which isolates the source from the load in order to maintain the solar panel voltage at the MPPV. MPPTs are implemented with DC/DC converters and can be seen as impedance converters which match the high impedance of the solar panel (about 13Ω on Fox-1) to the payload which is usually much higher (low power needs) or much lower (high power needs) impedance. Used as an intermediate translator of impedances, the MPPT serves to decouple payload needs from solar panel operating point.

FOX-1 Maximum Power Point Tracker



NOTES

* This MPPT implements a set-point constant voltage tracking algorithm based on panel temperature.
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design	
Brent Salmi, KB1LQD	
Bryce Salmi, KB1LQC	
The Radio Amateur Satellite Corporation	
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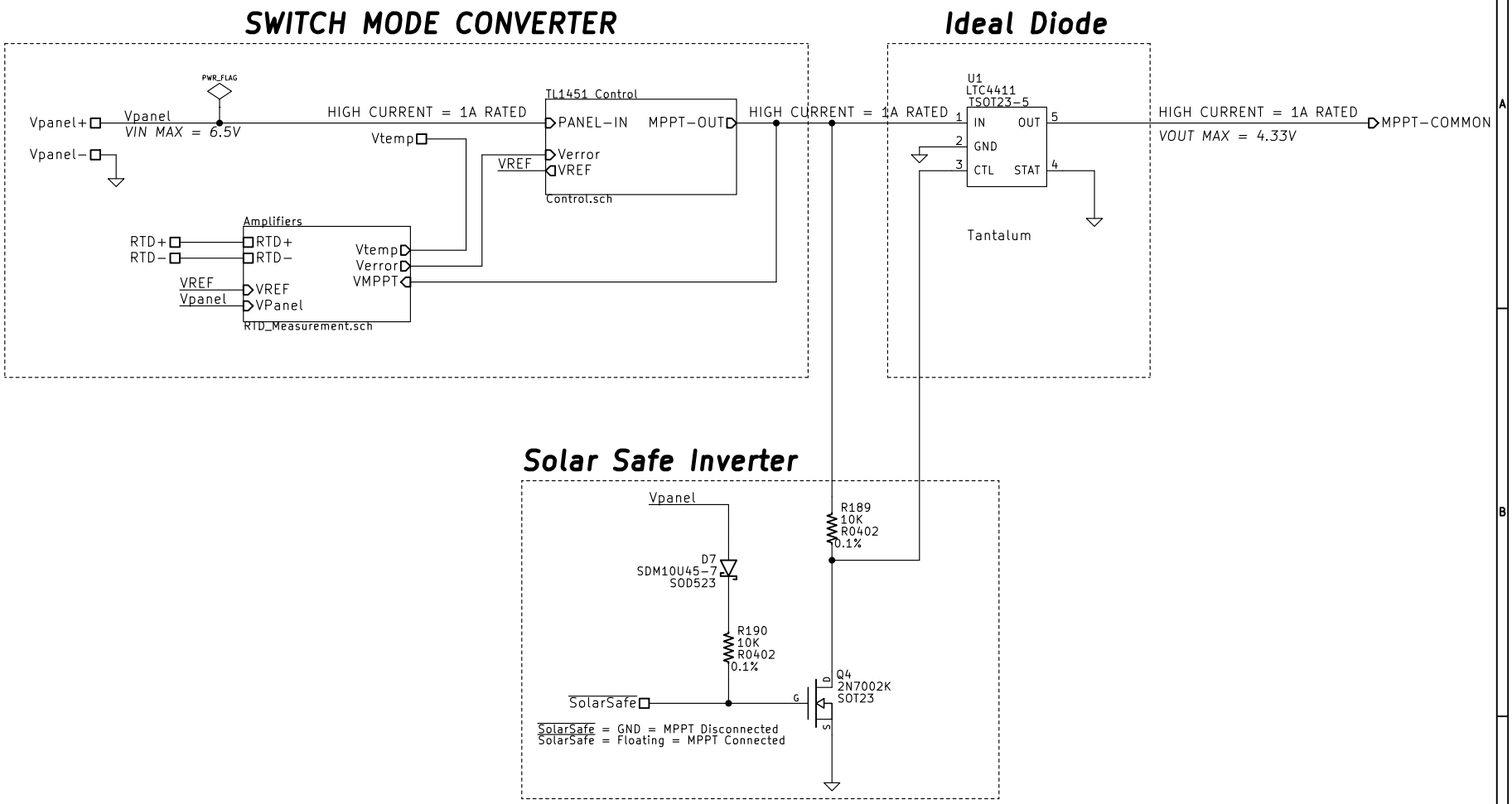
KiCad E.D.A.	Id: 1/37



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* NASA derating taken into account, not gauranteed

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Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
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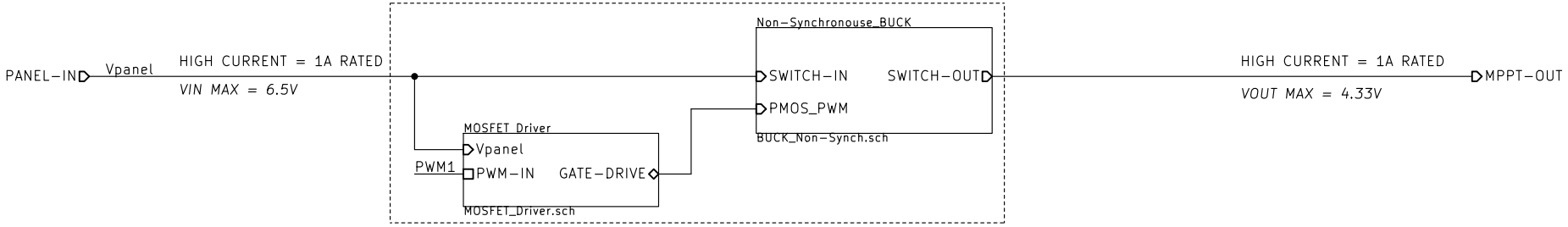
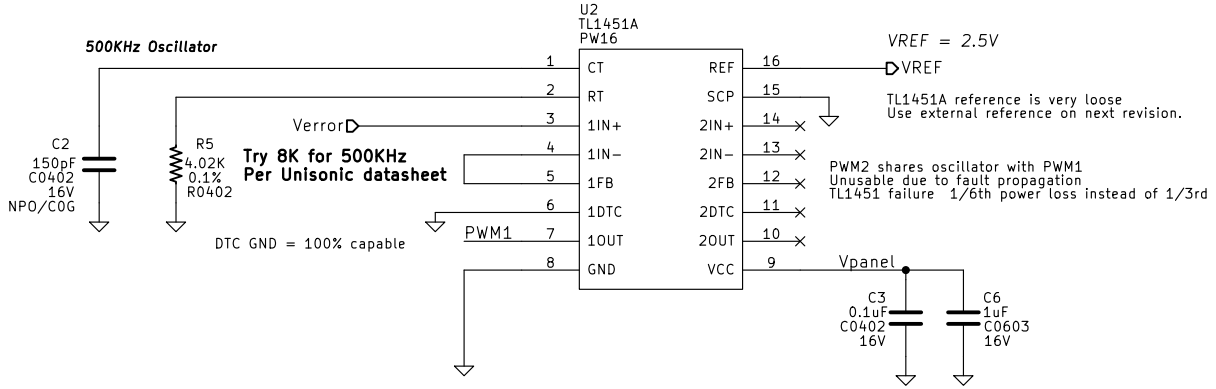
Switch Mode Converter





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Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
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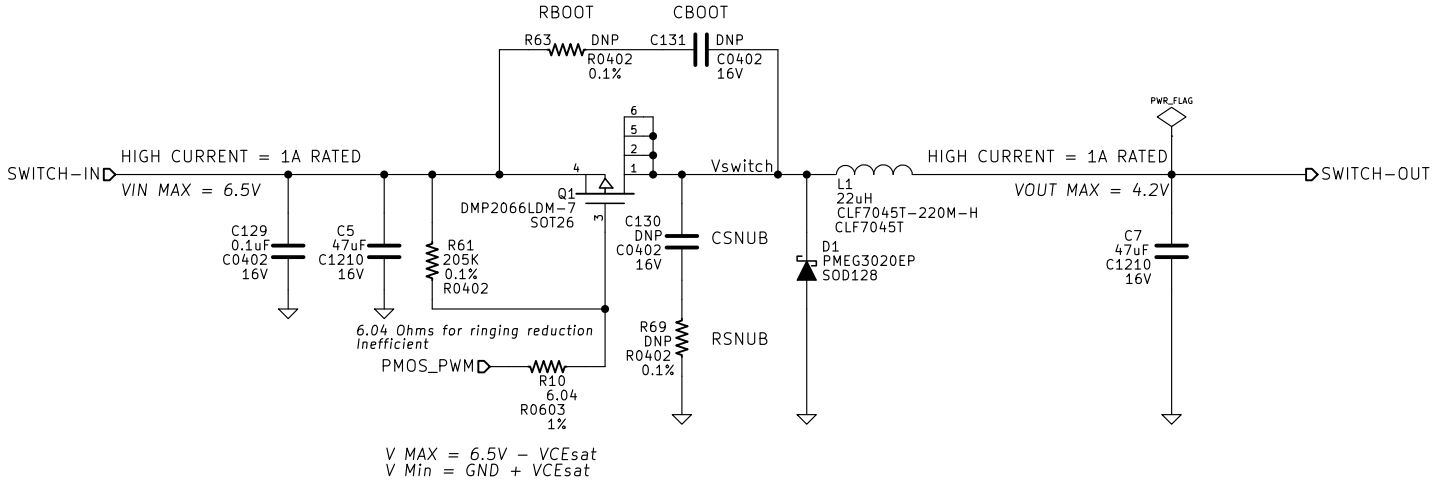
KiCad E.D.A.		Id: 3/37

500 KHz Step-Down Buck Converter



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* Parts not yet NASA derated.

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Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
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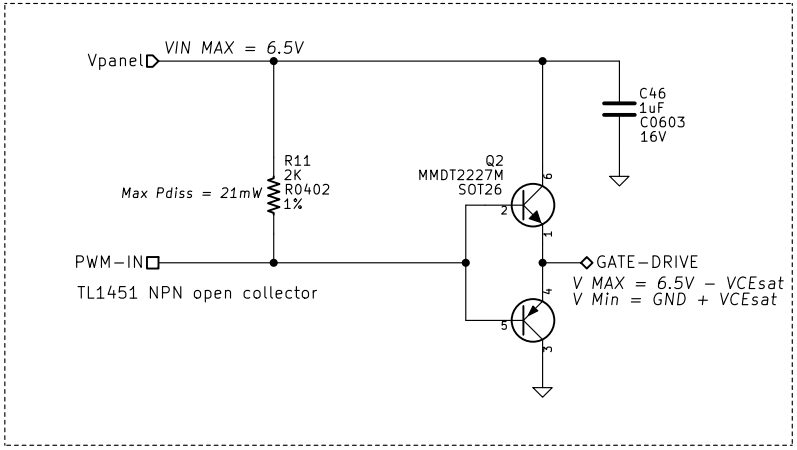
TOTEM POLE MOSFET DRIVER



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* Parts not yet NASA derated.

Based on Rochester Institute of Technology P13271 Design Brent Salmi, KB1LQD Bryce Salmi, KB1LQC *The Radio Amateur Satellite Corporation*		
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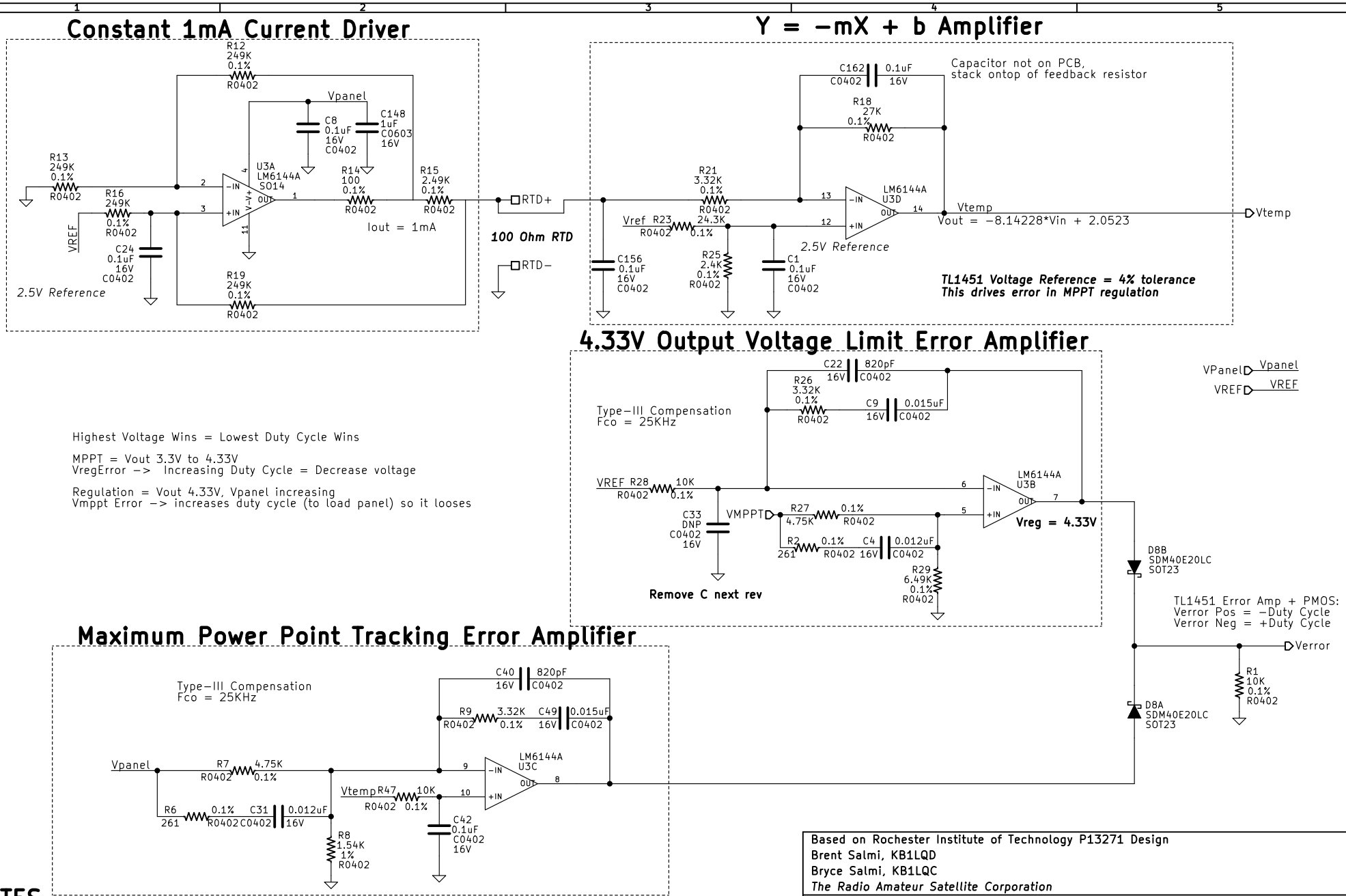

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Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
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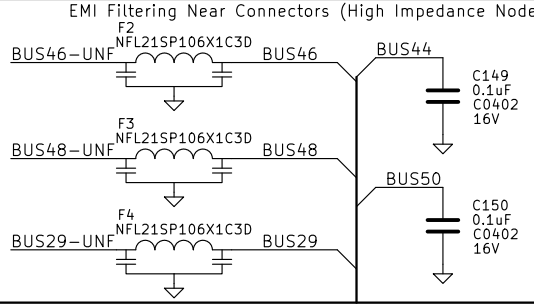

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Pmax = 2.53W

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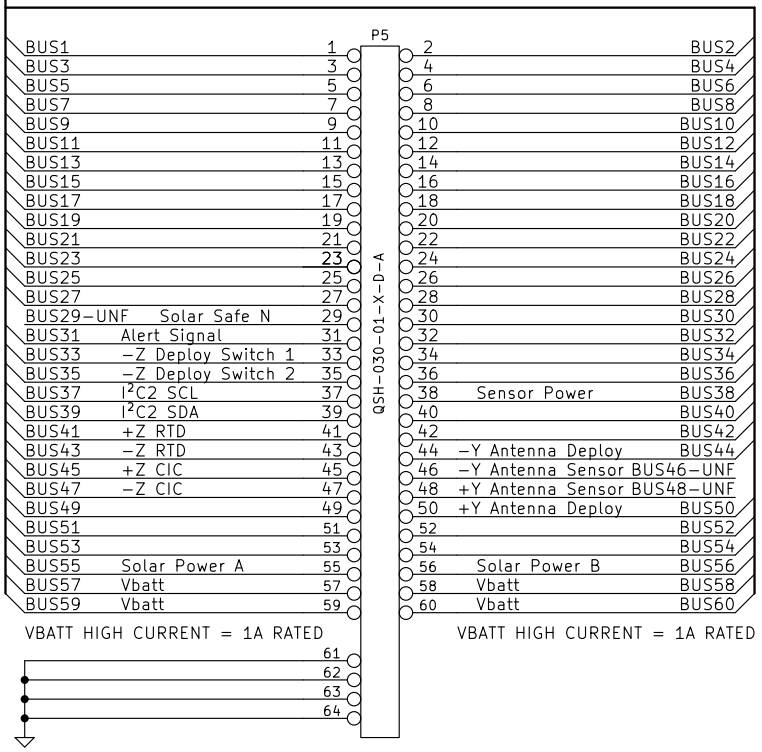
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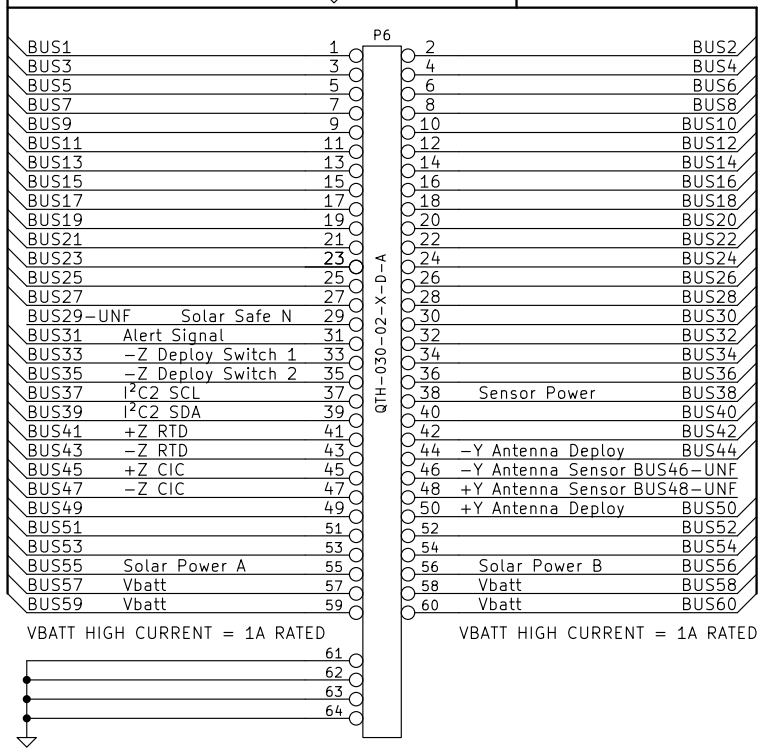
QSH-030-01-X-D-A
BUS1 1 2 BUS2
BUS3 3 4 BUS4
BUS5 5 6 BUS6
BUS7 7 8 BUS8
BUS9 9 10 BUS10
BUS11 11 12 BUS12
BUS13 13 14 BUS14
BUS15 15 16 BUS16
BUS17 17 18 BUS18
BUS19 19 20 BUS20
BUS21 21 22 BUS22
BUS23 23 24 BUS24
BUS25 25 26 BUS26
BUS27 27 28 BUS28
BUS29–UNF Solar Safe N 29 30 BUS30
BUS31 Alert Signal 31 32 BUS32
BUS33 –Z Deploy Switch 1 33 34 BUS34
BUS35 –Z Deploy Switch 2 35 36 BUS36
BUS37 I²C2 SCL 37 38 Sensor Power BUS38
BUS39 I²C2 SDA 39 40 BUS40
BUS41 +Z RTD 41 42 BUS42
BUS43 –Z RTD 43 44 –Y Antenna Deploy BUS44
BUS45 +Z CIC 45 46 –Y Antenna Sensor BUS46–UNF
BUS47 –Z CIC 47 48 +Y Antenna Sensor BUS48–UNF
BUS49 49 50 +Y Antenna Deploy BUS50
BUS51 51 52 BUS52
BUS53 53 54 BUS54
BUS55 Solar Power A 55 56 Solar Power B BUS56
BUS57 Vbatt 57 58 Vbatt BUS58
BUS59 Vbatt 59 60 Vbatt BUS60
VBATT HIGH CURRENT = 1A RATED
VBATT HIGH CURRENT = 1A RATED
61
62
63
64

BUS[1..60]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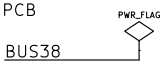
BUS9 9 10 BUS10
BUS11 11 12 BUS12
BUS13 13 14 BUS14
BUS15 15 16 BUS16
BUS17 17 18 BUS18
BUS19 19 20 BUS20
BUS21 21 22 BUS22
BUS23 23 24 BUS24
BUS25 25 26 BUS26
BUS27 27 28 BUS28
BUS29–UNF Solar Safe N 29 30 BUS30
BUS31 Alert Signal 31 32 BUS32
BUS33 –Z Deploy Switch 1 33 34 BUS34
BUS35 –Z Deploy Switch 2 35 36 BUS36
BUS37 I²C2 SCL 37 38 Sensor Power BUS38
BUS39 I²C2 SDA 39 40 BUS40
BUS41 +Z RTD 41 42 BUS42
BUS43 –Z RTD 43 44 –Y Antenna Deploy BUS44
BUS45 +Z CIC 45 46 –Y Antenna Sensor BUS46–UNF
BUS47 –Z CIC 47 48 +Y Antenna Sensor BUS48–UNF
BUS49 49 50 +Y Antenna Deploy BUS50
BUS51 51 52 BUS52
BUS53 53 54 BUS54
BUS55 Solar Power A 55 56 Solar Power B BUS56
BUS57 Vbatt 57 58 Vbatt BUS58
BUS59 Vbatt 59 60 Vbatt BUS60
VBATT HIGH CURRENT = 1A RATED
VBATT HIGH CURRENT = 1A RATED
61
62
63
64

BUS38 Sensor Power is driven by the IHU PCB



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Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
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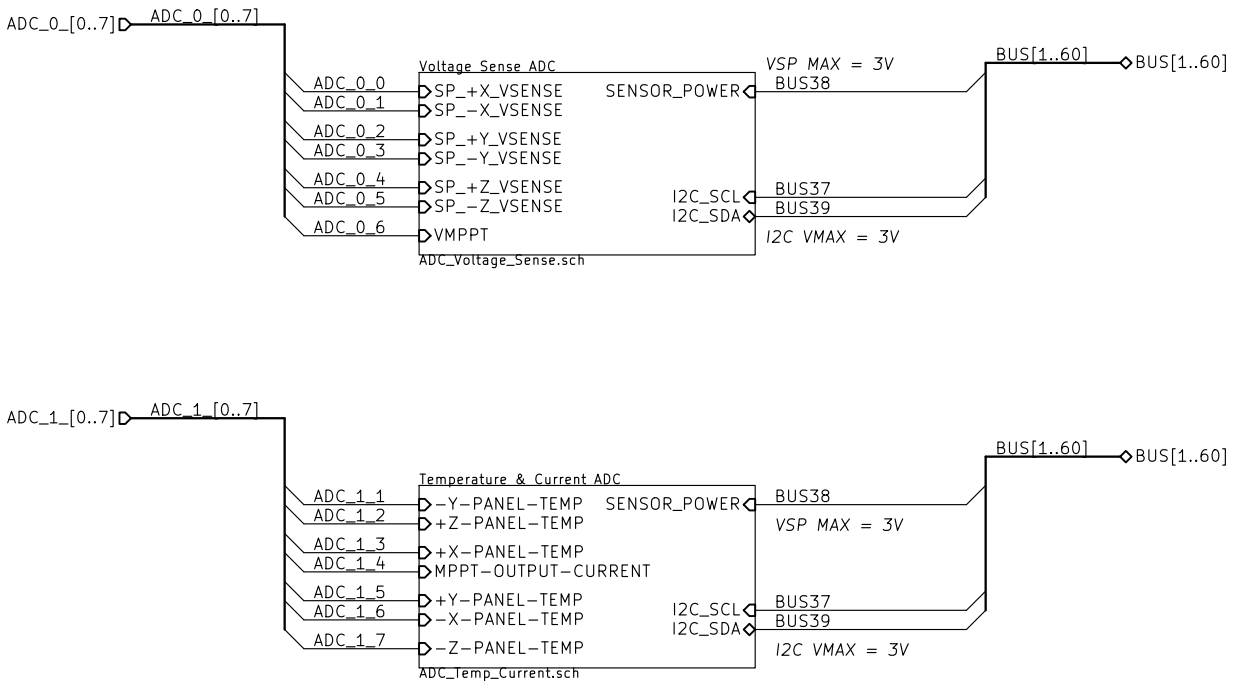

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Based on Rochester Institute of Technology P13271 Design Brent Salmi, KB1LQD Bryce Salmi, KB1LQC *The Radio Amateur Satellite Corporation*		
File: ADC_Channels.sch Sheet: /ADC Channels/		
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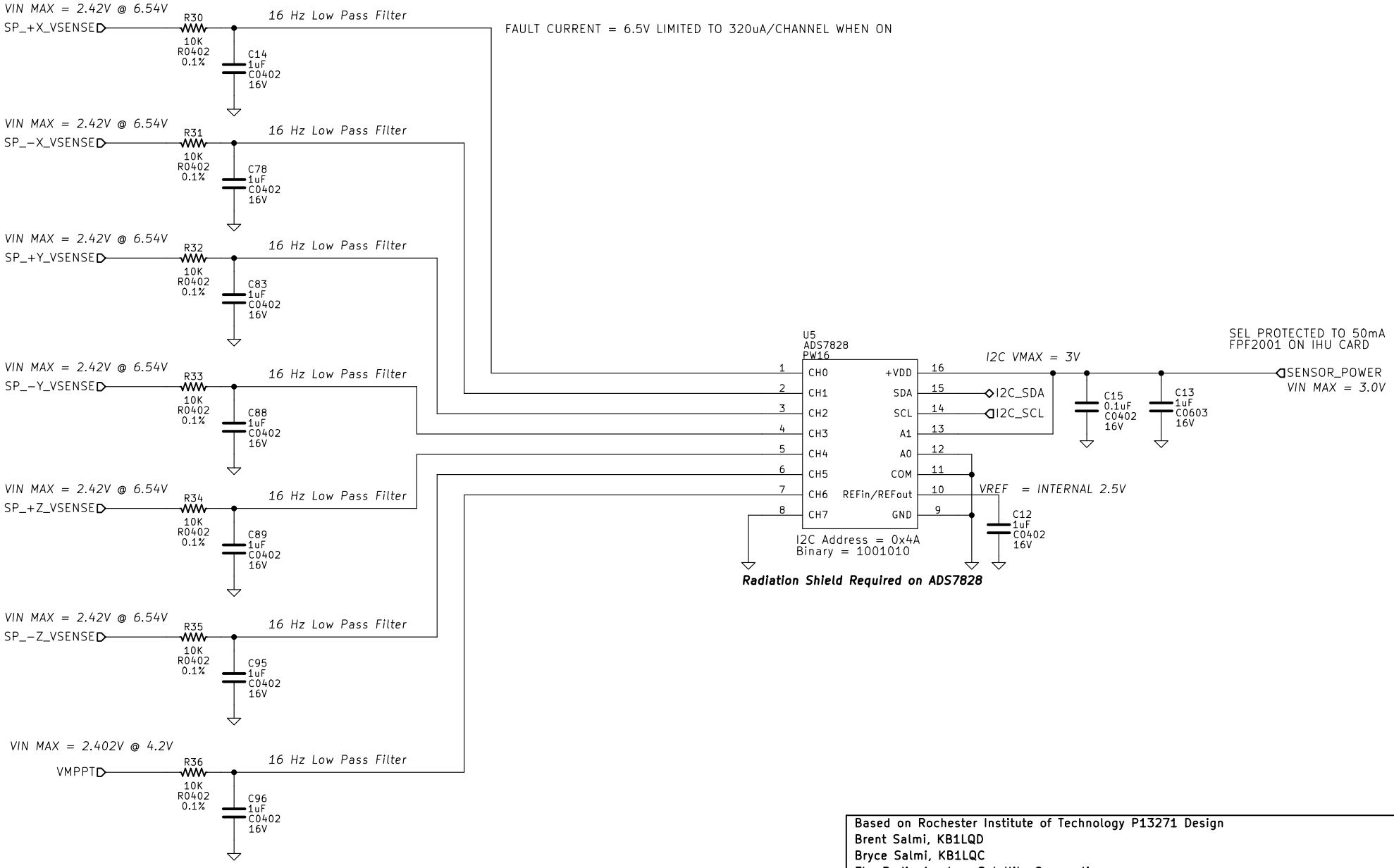

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Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: ADC_Voltage_Sense.sch		
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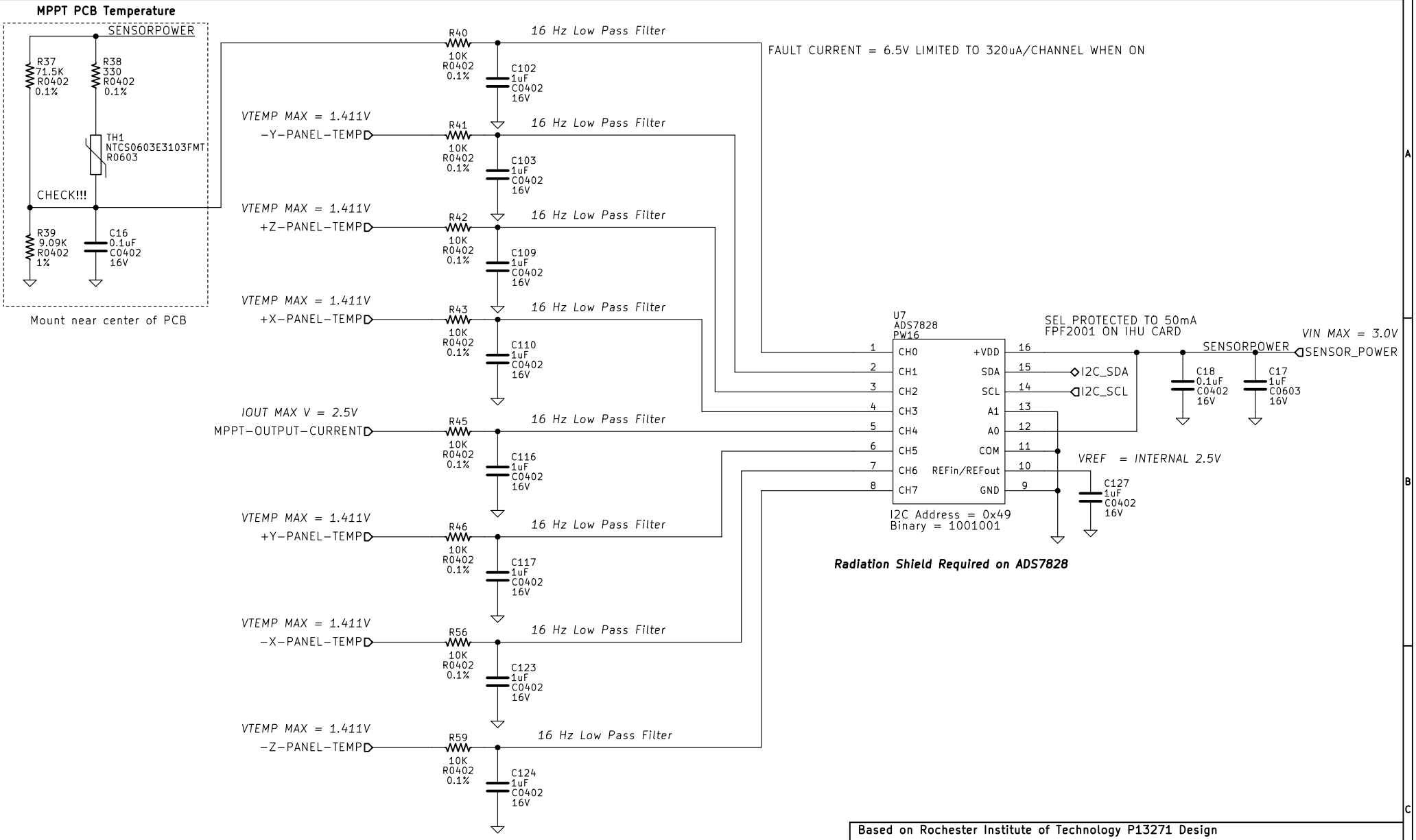

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Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: ADC_Temp_Current.sch		
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Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
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PANEL VOLTAGE TELEMETRY ADC SCALING

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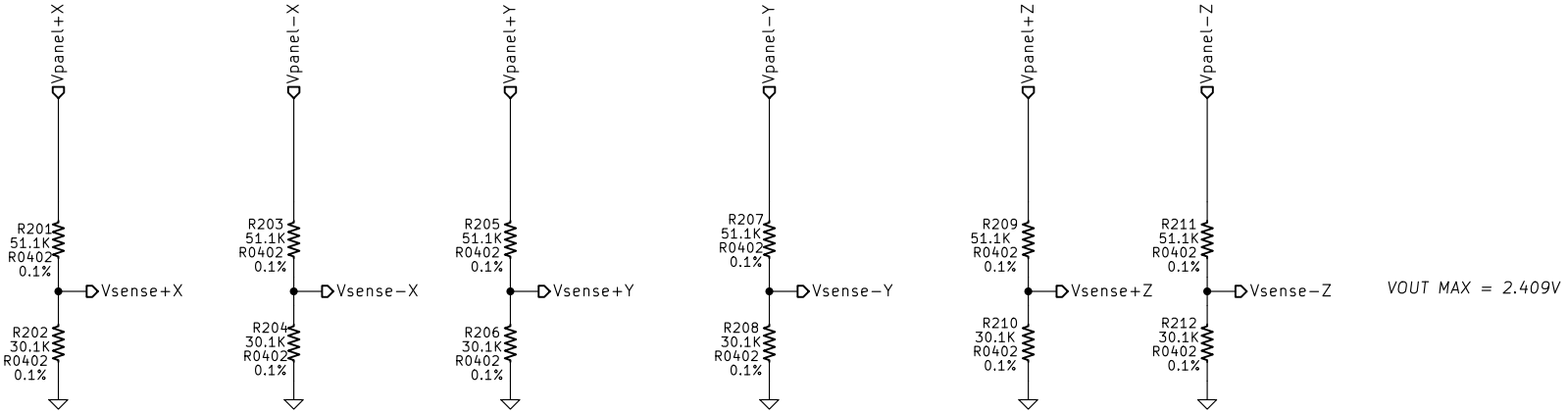

VOUT MAX = 2.409V

NOTES

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The Radio Amateur Satellite Corporation		
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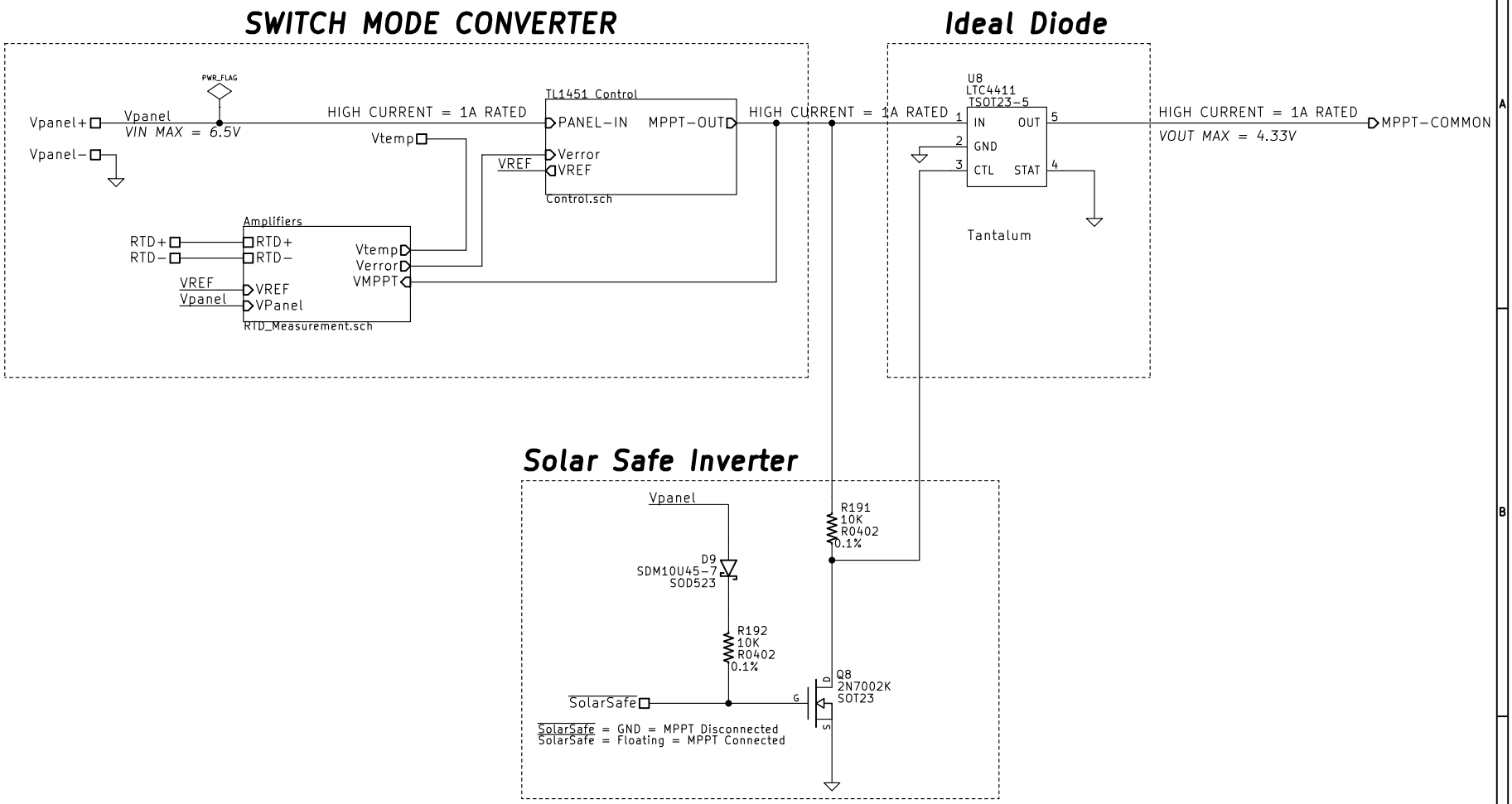

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Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
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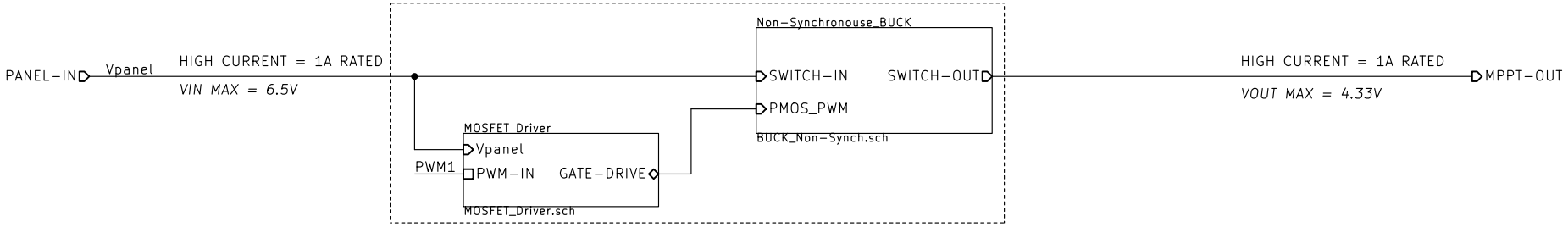
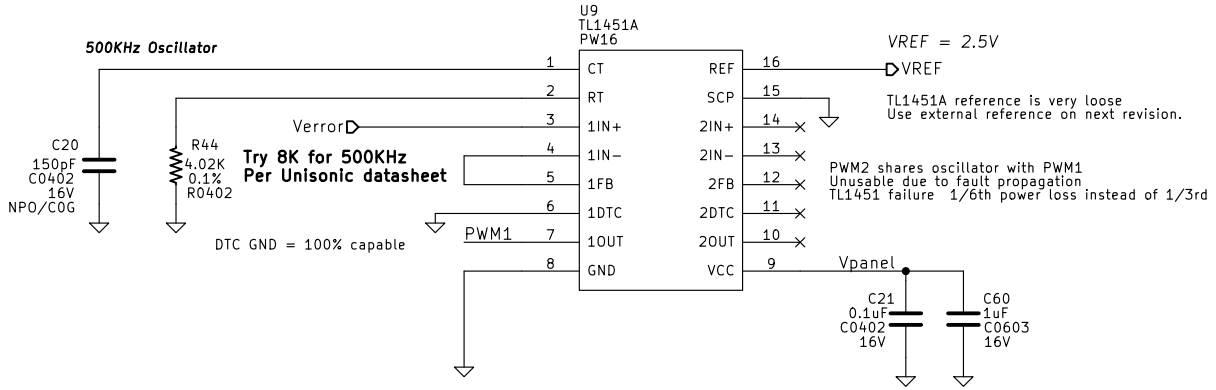
Switch Mode Converter





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* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: Control.sch		
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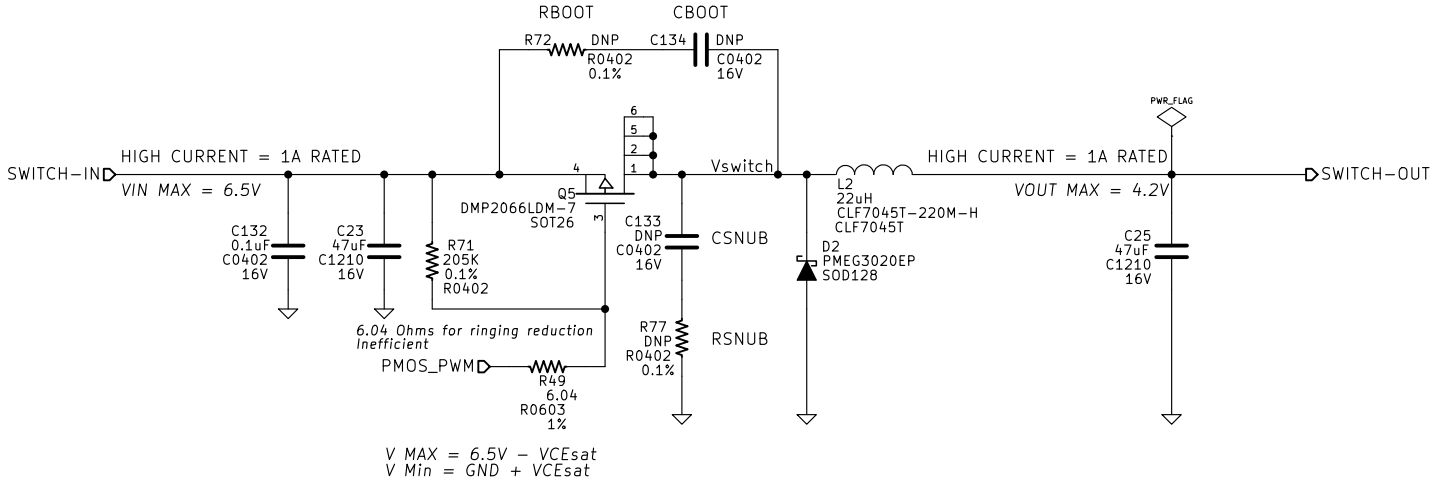
KiCad E.D.A.		Id: 13/37

500 KHz Step-Down Buck Converter

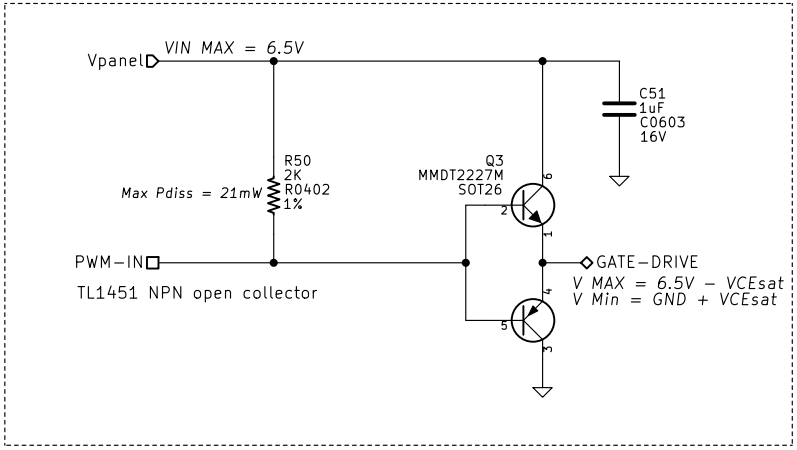


NOTES

* This MPPT implements a set-point constant voltage tracking algorithm based on panel temperature.
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* Parts not yet NASA derated.

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: BUCK_Non-Synch.sch		
Sheet: /MPPT_String_X-/TL1451 Control/Non-Synchronouse_BUCK/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 14/37

TOTEM POLE MOSFET DRIVER



NOTES

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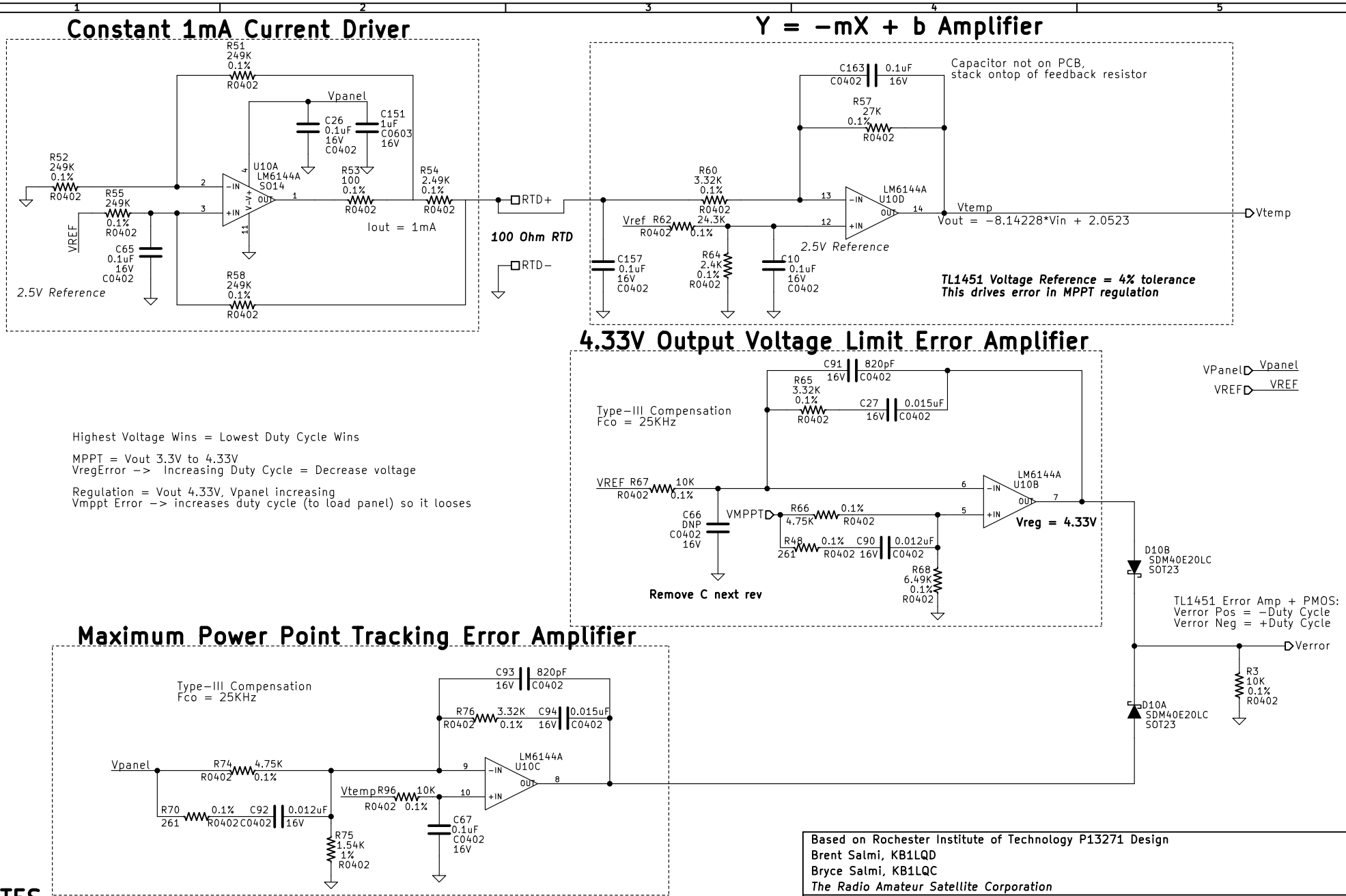
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* Parts not yet NASA derated.

Based on Rochester Institute of Technology P13271 Design Brent Salmi, KB1LQD Bryce Salmi, KB1LQC *The Radio Amateur Satellite Corporation*		
File: MOSFET_Driver.sch Sheet: /MPPT_String_X-/TL1451 Control/MOSFET Driver/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 15/37



NOTES

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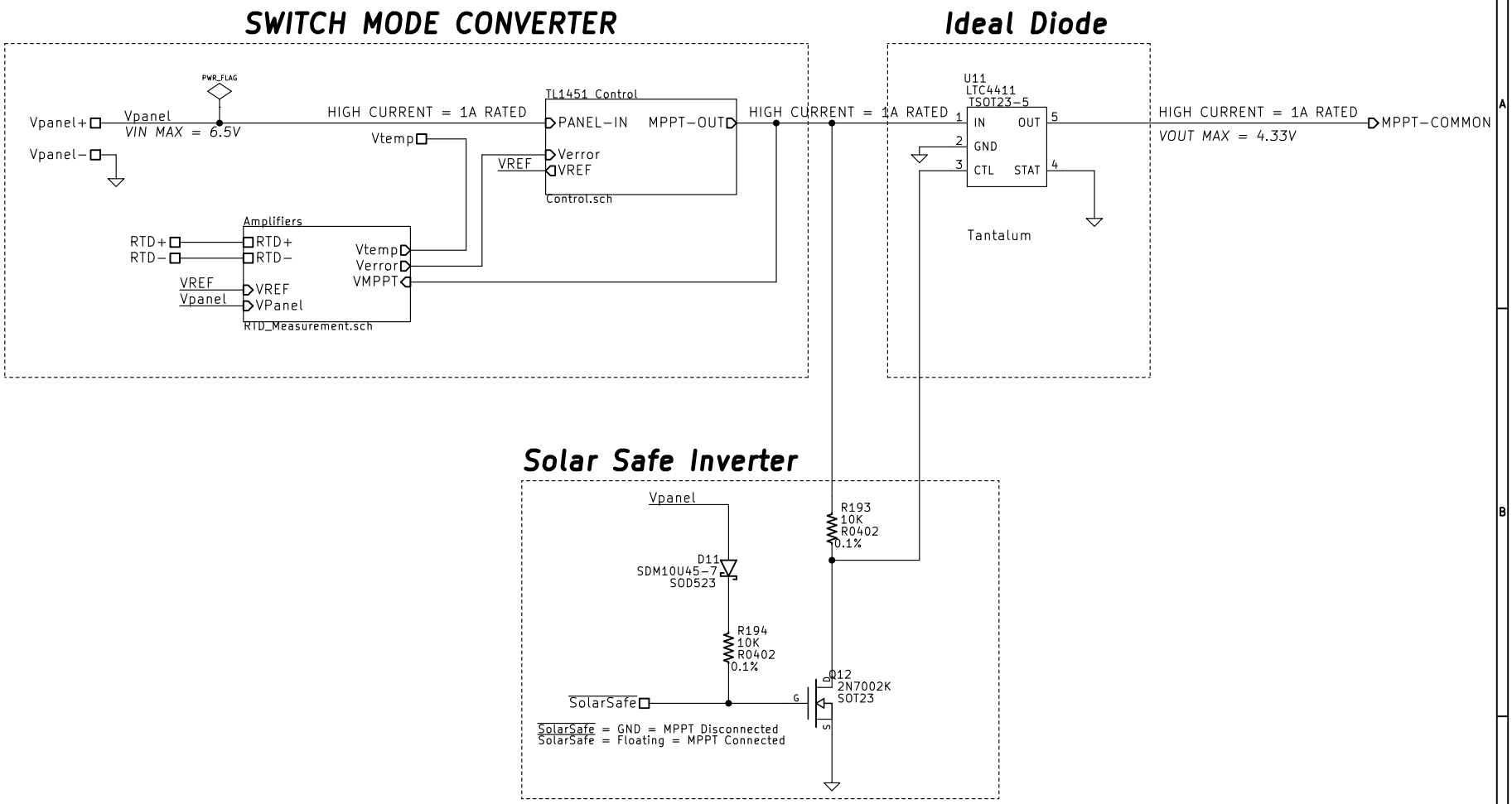
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: RTD_Measurement.sch		
Sheet: /MPPT_String_X−/Amplifiers/		
Title: Fox−1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 16/37

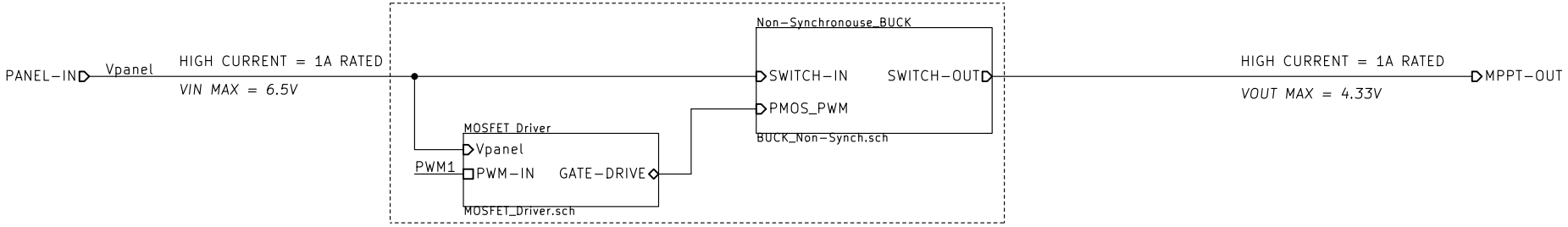


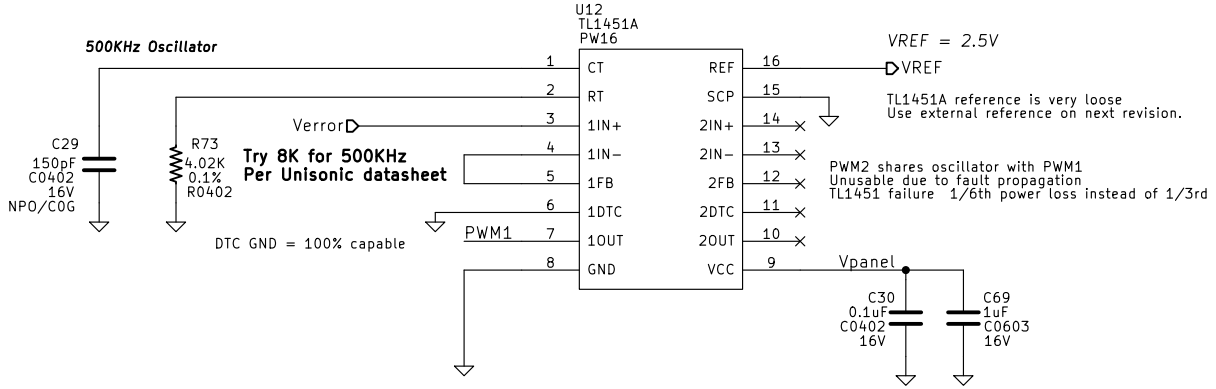
NOTES

* This MPPT implements a set−point constant voltage tracking algorithm based on panel temperature.
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: MPPT_String.sch		
Sheet: /MPPT_String_Y+/		
Title: Fox−1 Maximum Power Point Tracker		
Size: A	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 17/37

Switch Mode Converter





NOTES

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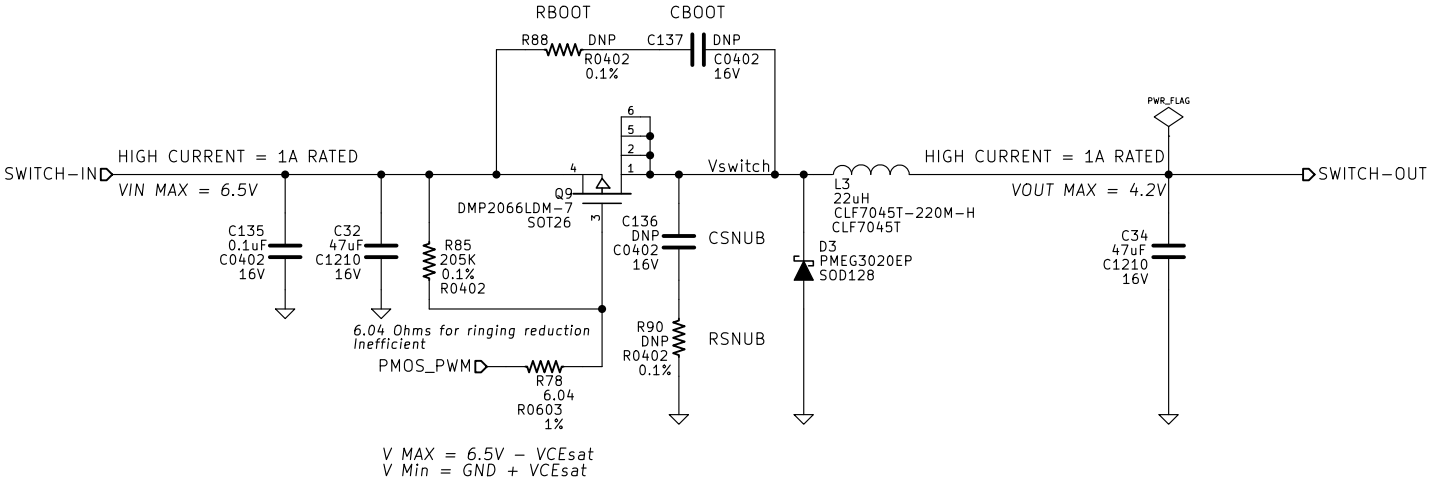
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: Control.sch		
Sheet: /MPPT_String_Y+/TL1451 Control/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 18/37

500 KHz Step-Down Buck Converter

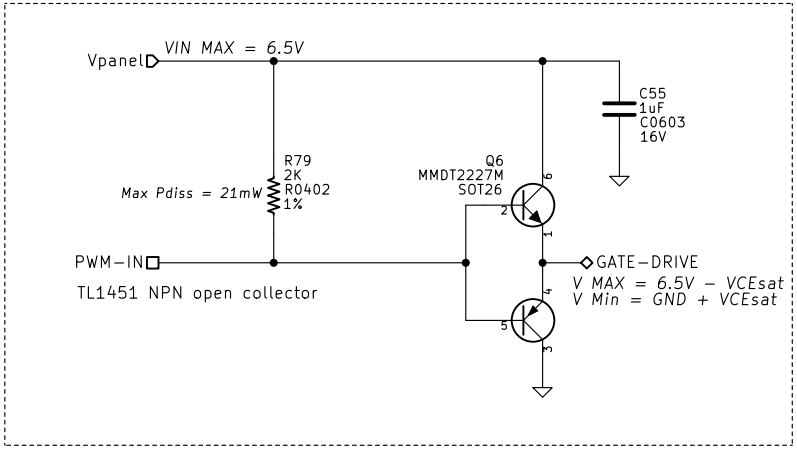


NOTES

* This MPPT implements a set-point constant voltage tracking algorithm based on panel temperature.
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* Parts not yet NASA derated.

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: BUCK_Non-Synch.sch		
Sheet: /MPPT_String_Y+/TL1451 Control/Non-Synchronouse_BUCK/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 19/37

TOTEM POLE MOSFET DRIVER



NOTES

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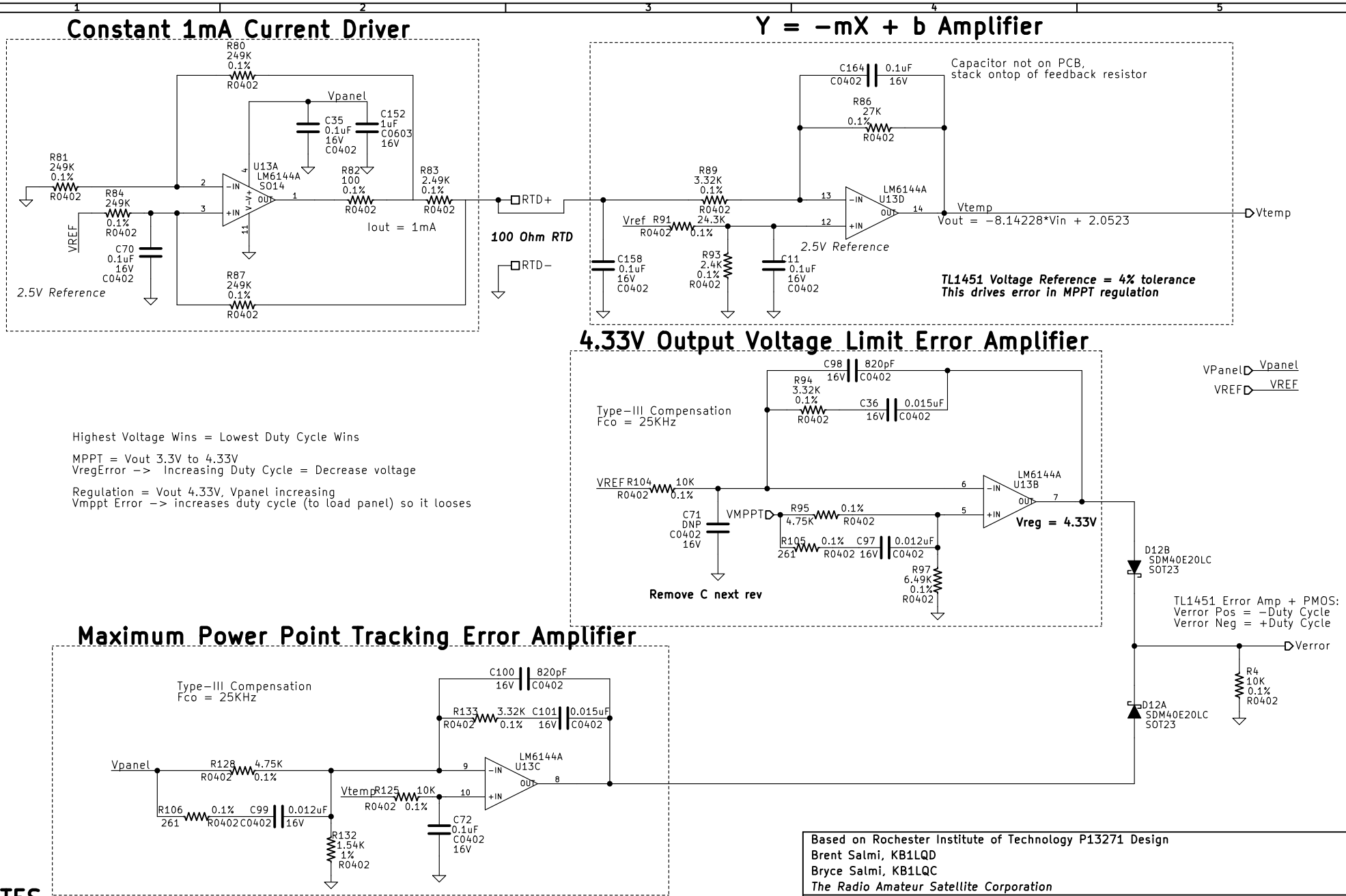
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* Parts not yet NASA derated.

Based on Rochester Institute of Technology P13271 Design Brent Salmi, KB1LQD Bryce Salmi, KB1LQC *The Radio Amateur Satellite Corporation*		
File: MOSFET_Driver.sch Sheet: /MPPT_String_Y+/TL1451 Control/MOSFET Driver/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 20/37



NOTES

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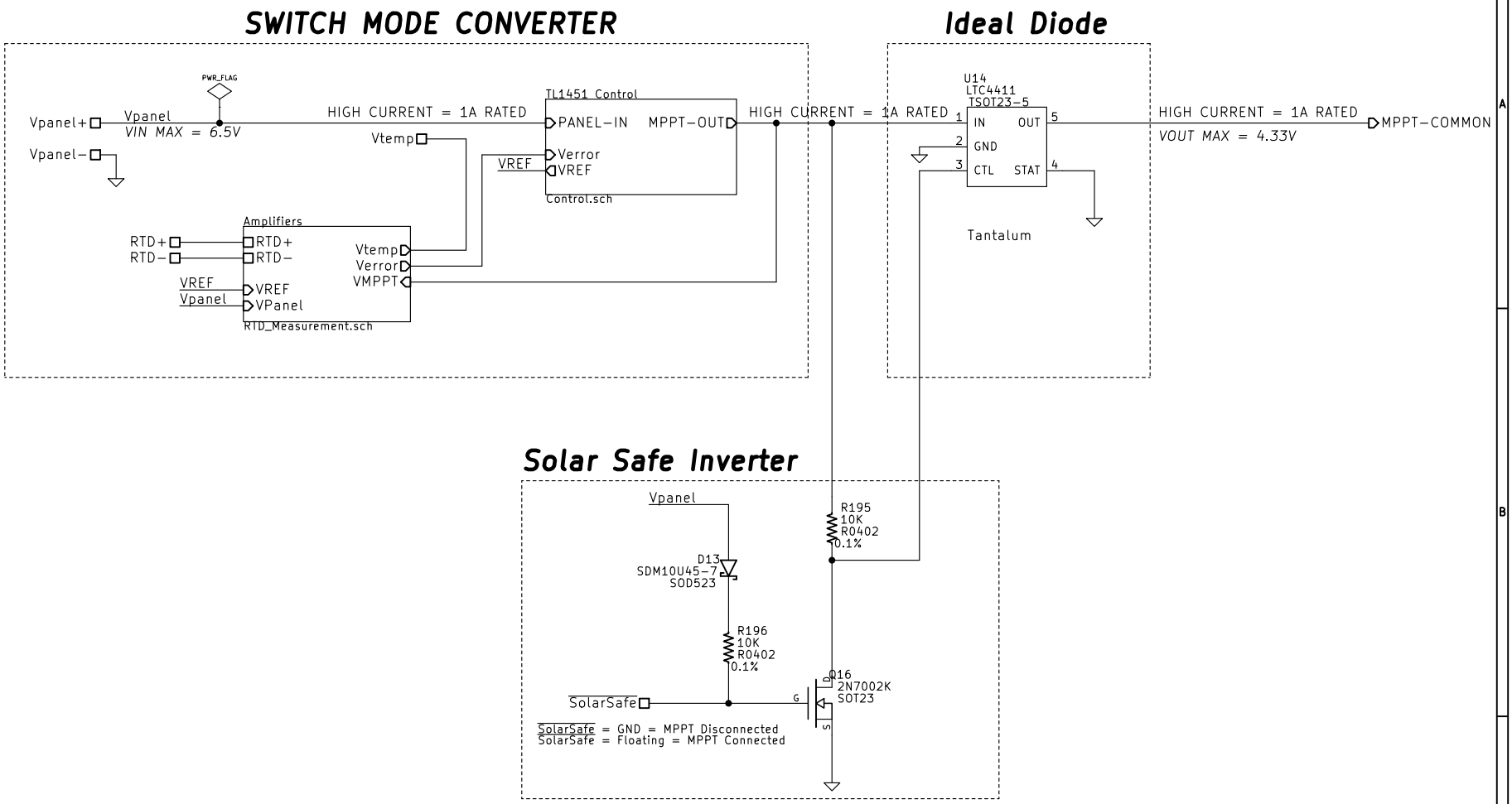
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: RTD_Measurement.sch		
Sheet: /MPPT_String_Y+/Amplifiers/		
Title: Fox−1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 21/37



NOTES

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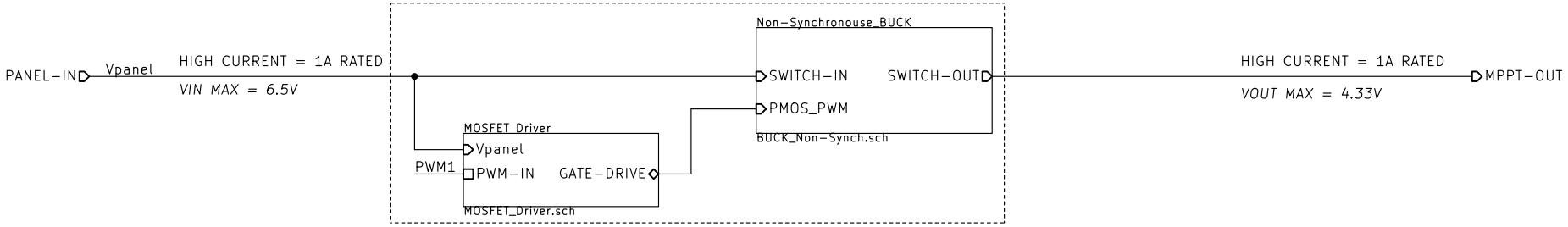
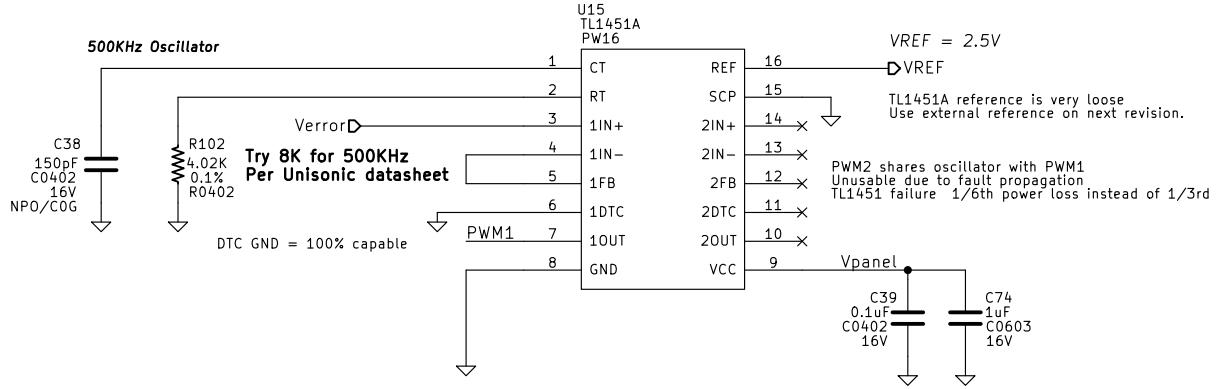
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: MPPT_String.sch		
Sheet: /MPPT_String_Y−/		
Title: Fox−1 Maximum Power Point Tracker		
Size: A	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 22/37

Switch Mode Converter





NOTES

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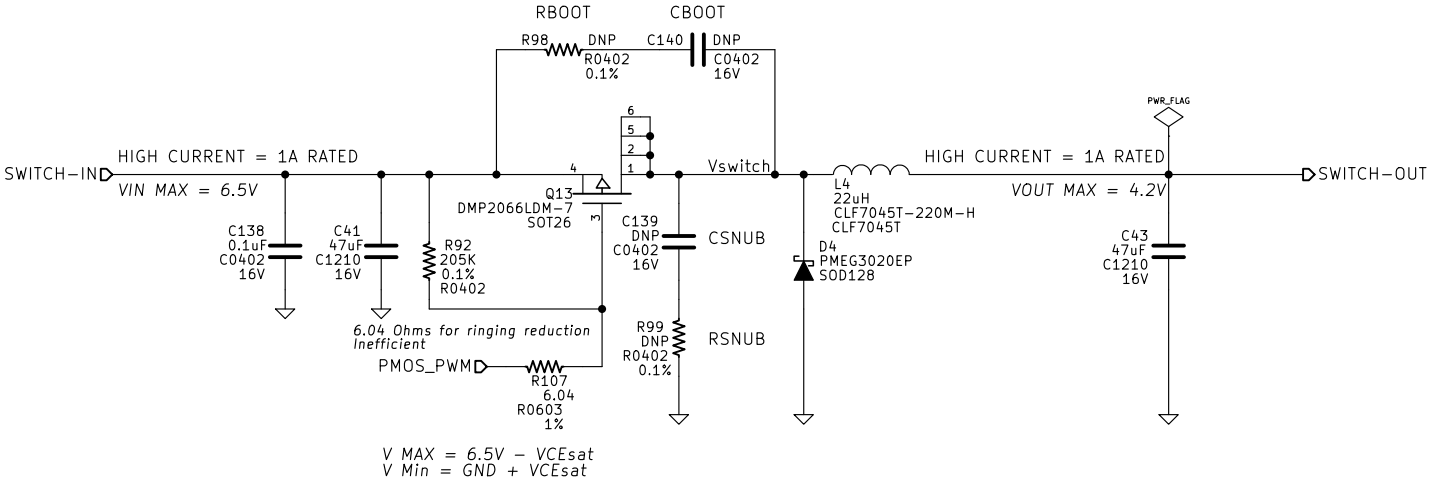
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: Control.sch		
Sheet: /MPPT_String_Y-/TL1451 Control/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 23/37

500 KHz Step-Down Buck Converter



NOTES

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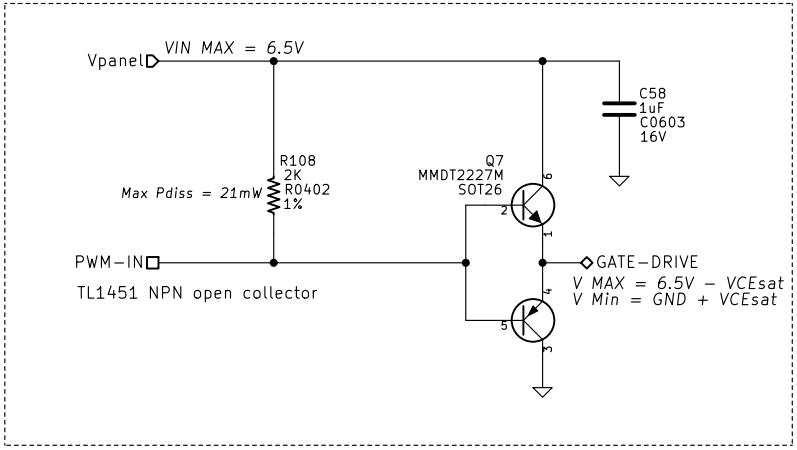
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* Parts not yet NASA derated.

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: BUCK_Non-Synch.sch		
Sheet: /MPPT_String_Y-/TL1451 Control/Non-Synchronouse_BUCK/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 24/37

TOTEM POLE MOSFET DRIVER



NOTES

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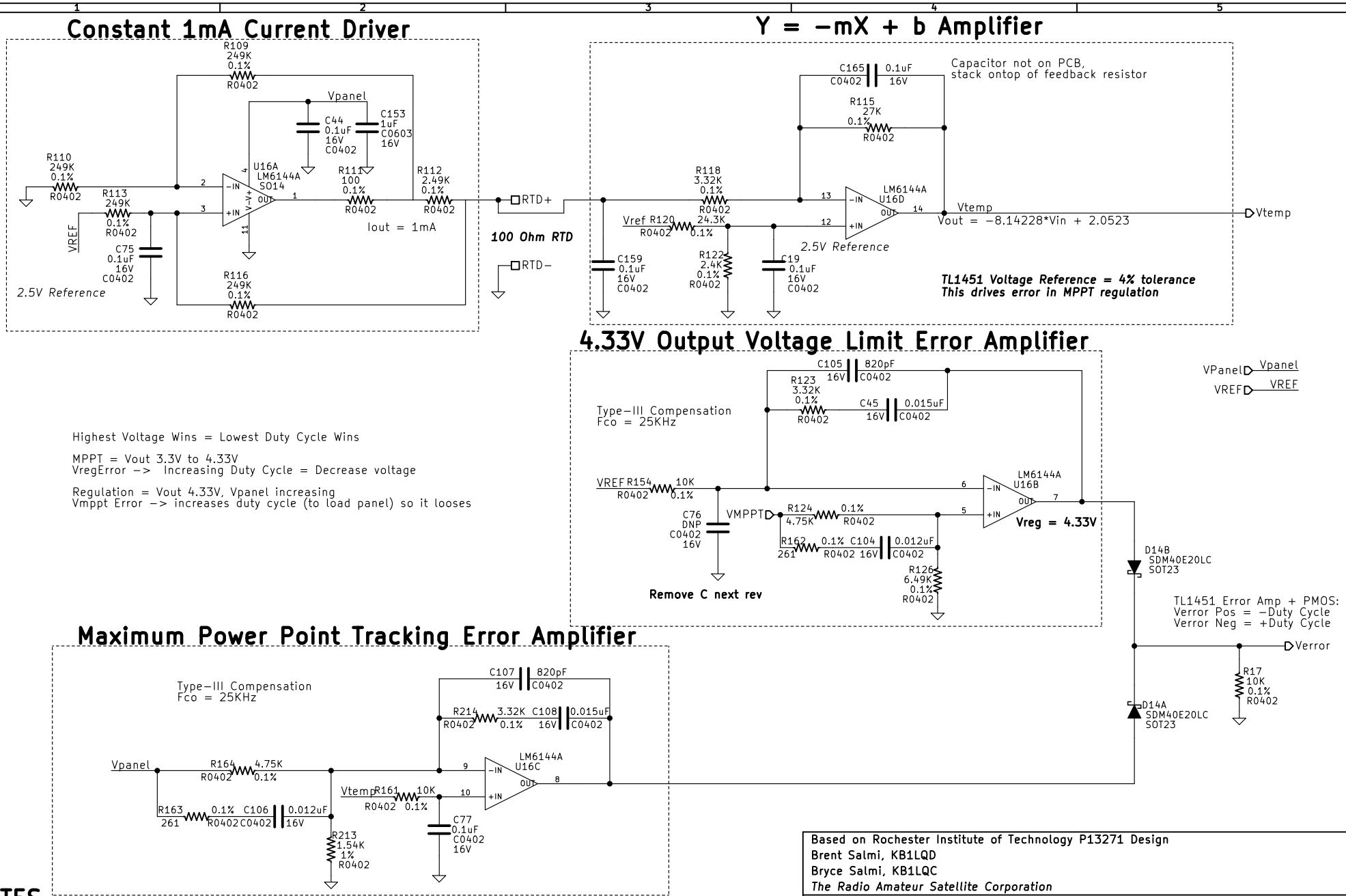
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* Parts not yet NASA derated.

Based on Rochester Institute of Technology P13271 Design Brent Salmi, KB1LQD Bryce Salmi, KB1LQC *The Radio Amateur Satellite Corporation*		
File: MOSFET_Driver.sch Sheet: /MPPT_String_Y-/TL1451 Control/MOSFET Driver/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 25/37



NOTES

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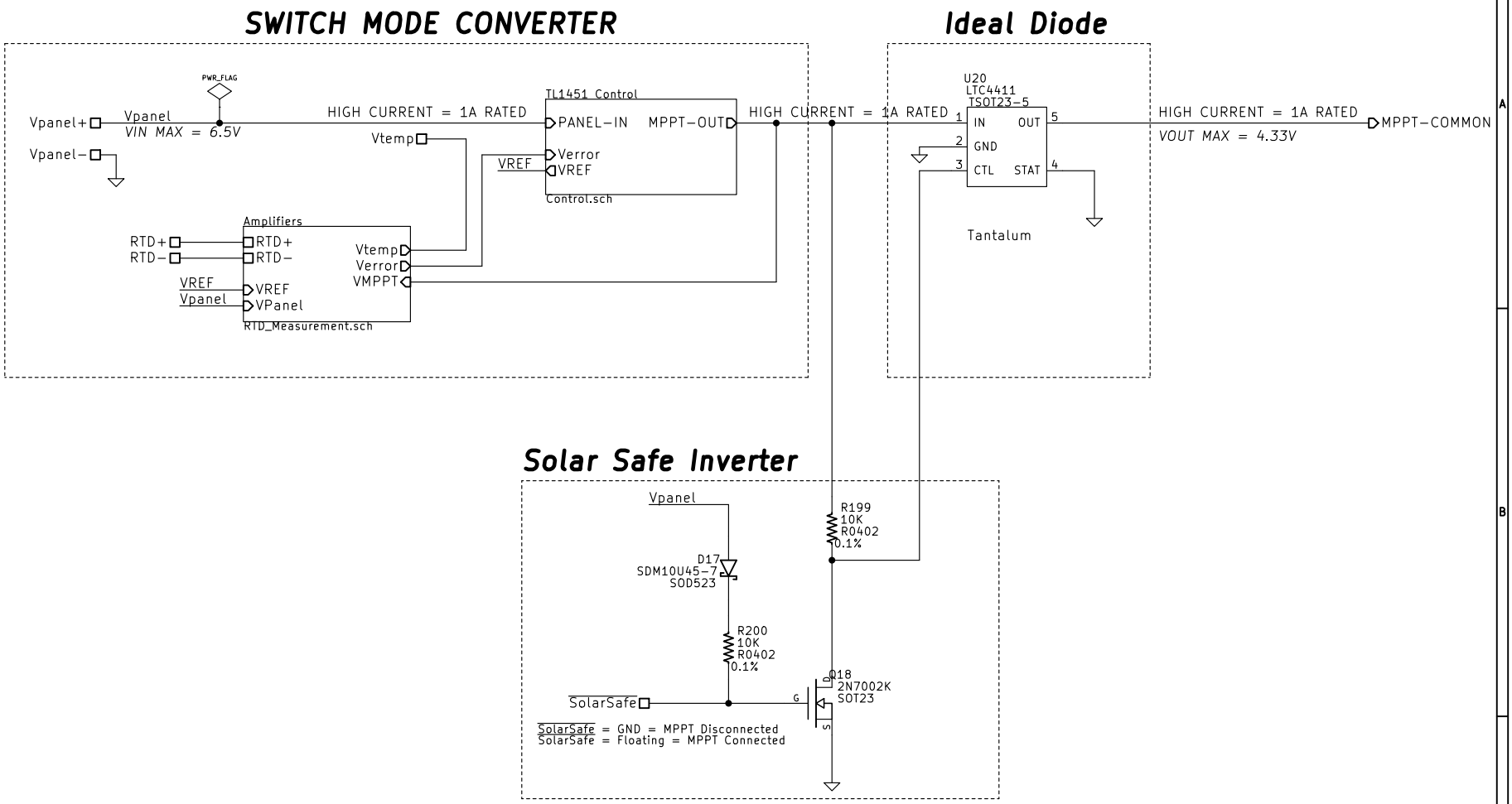
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: RTD_Measurement.sch		
Sheet: /MPPT_String_Y−/Amplifiers/		
Title: Fox−1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 26/37



NOTES

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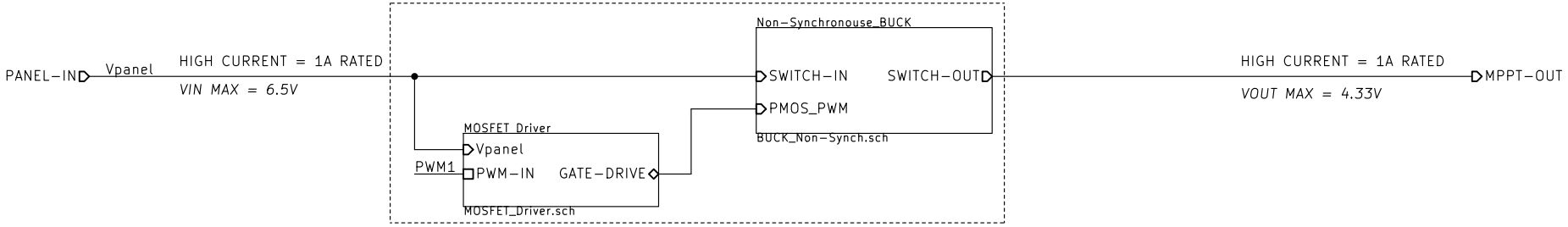
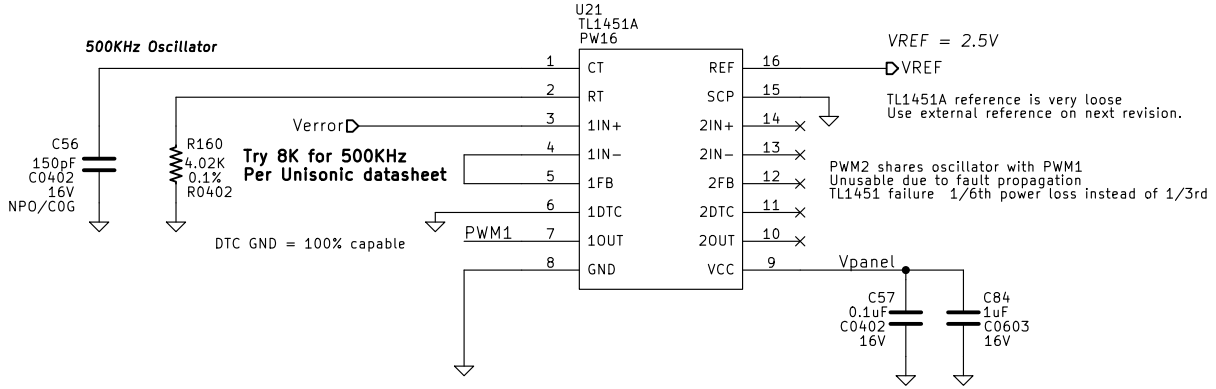
Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: MPPT_String.sch		
Sheet: /MPPT_String_Z−/		
Title: Fox−1 Maximum Power Point Tracker		
Size: A	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 27/37

Switch Mode Converter





NOTES

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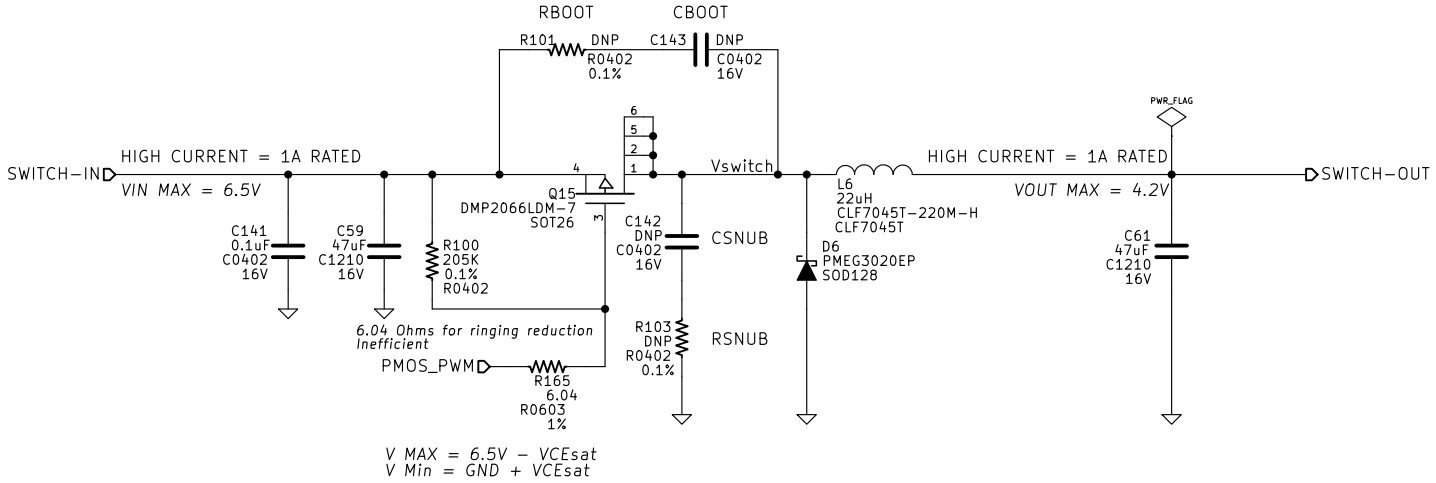
Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: Control.sch		
Sheet: /MPPT_String_Z-/TL1451 Control/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 28/37

500 KHz Step-Down Buck Converter



NOTES

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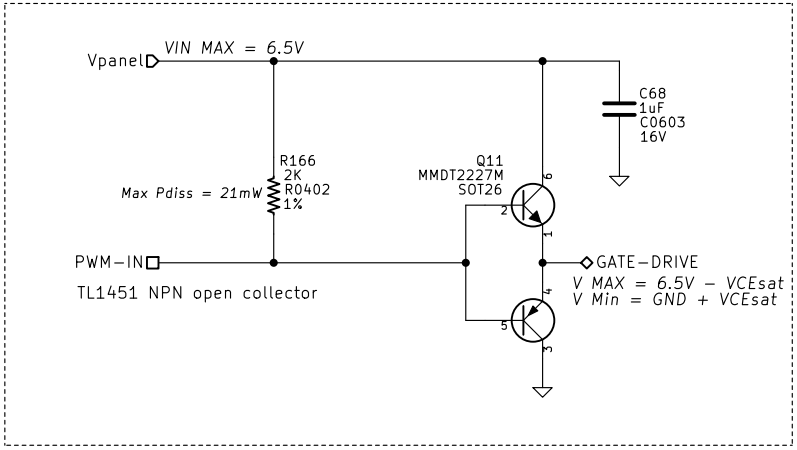
Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: BUCK_Non-Synch.sch		
Sheet: /MPPT_String_Z-/TL1451 Control/Non-Synchronouse_BUCK/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 29/37

TOTEM POLE MOSFET DRIVER



NOTES

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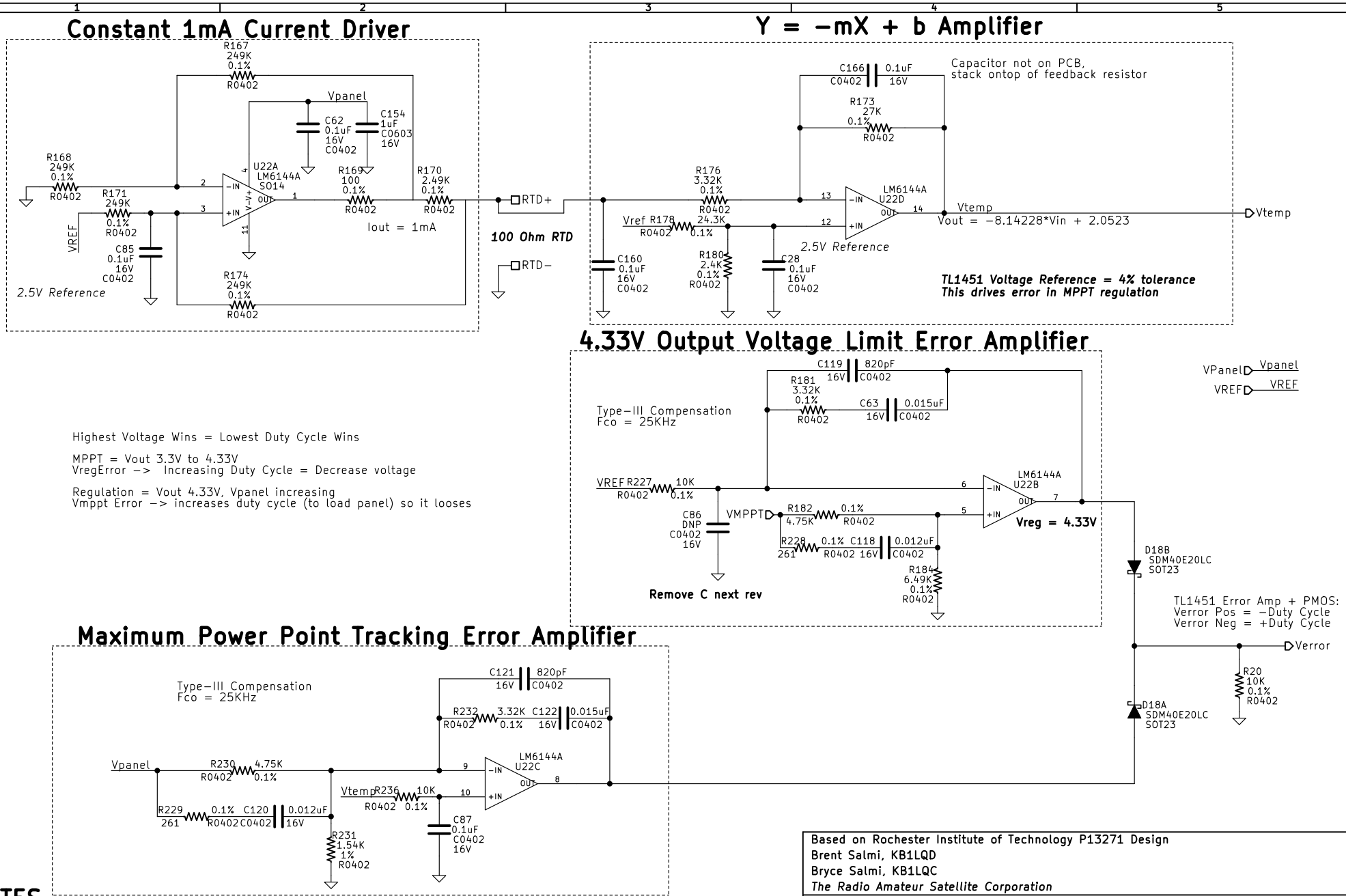
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* Parts not yet NASA derated.

Based on Rochester Institute of Technology P13271 Design Brent Salmi, KB1LQD Bryce Salmi, KB1LQC *The Radio Amateur Satellite Corporation*		
File: MOSFET_Driver.sch Sheet: /MPPT_String_Z-/TL1451 Control/MOSFET Driver/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 30/37



NOTES

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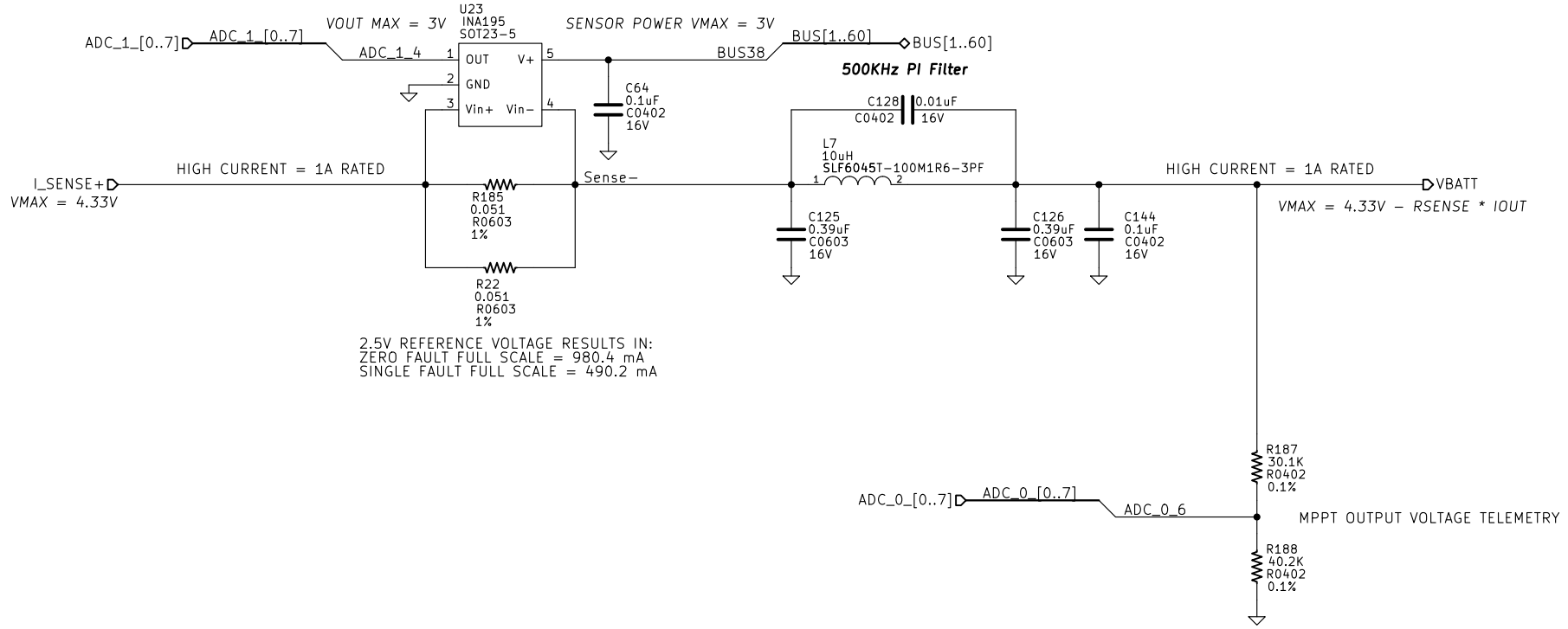
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: RTD_Measurement.sch		
Sheet: /MPPT_String_Z−/Amplifiers/		
Title: Fox−1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 31/37



NOTES

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* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
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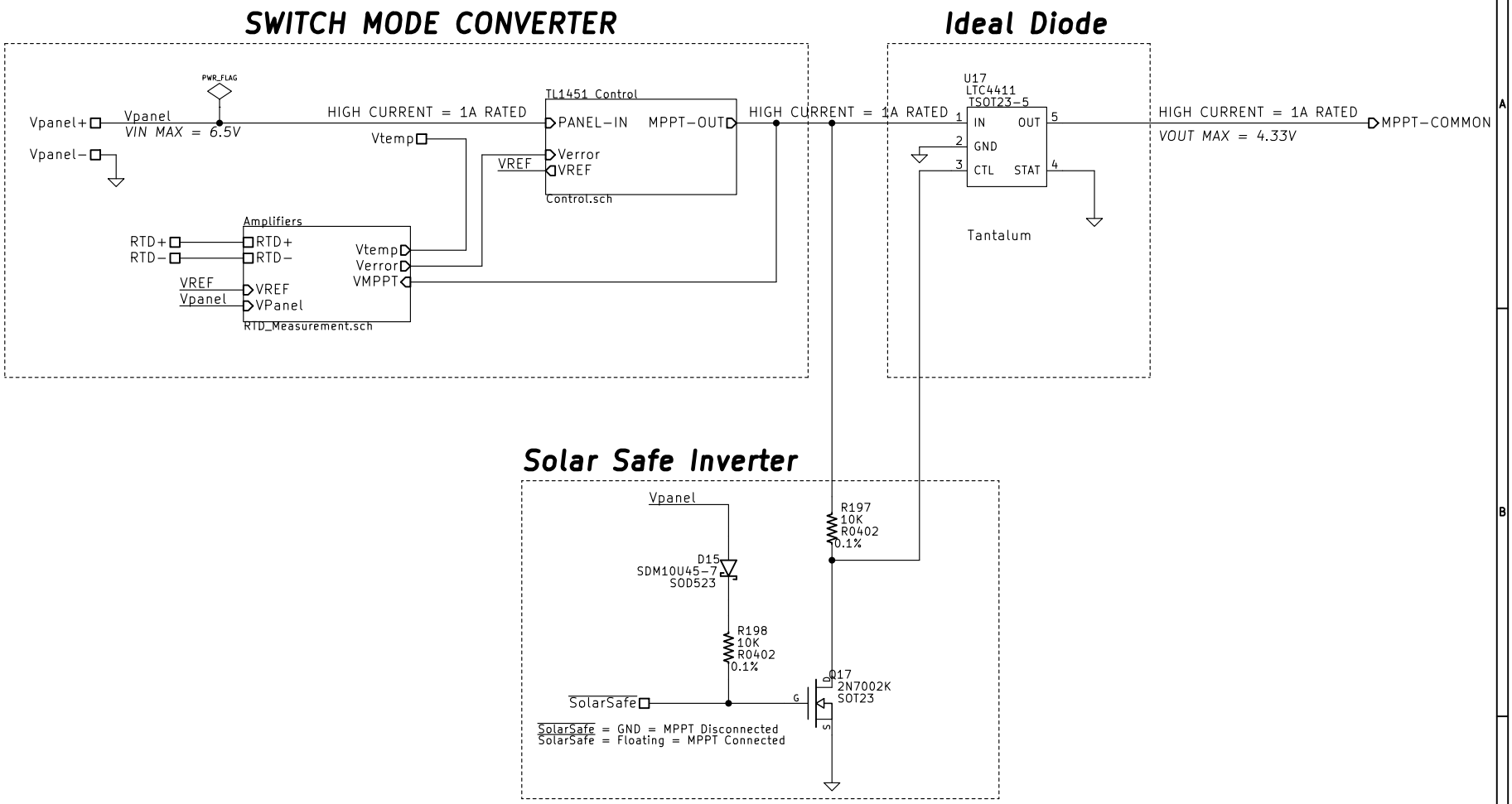
Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: Current_Sense.sch		
Sheet: /Current Sense/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 32/37



NOTES

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* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
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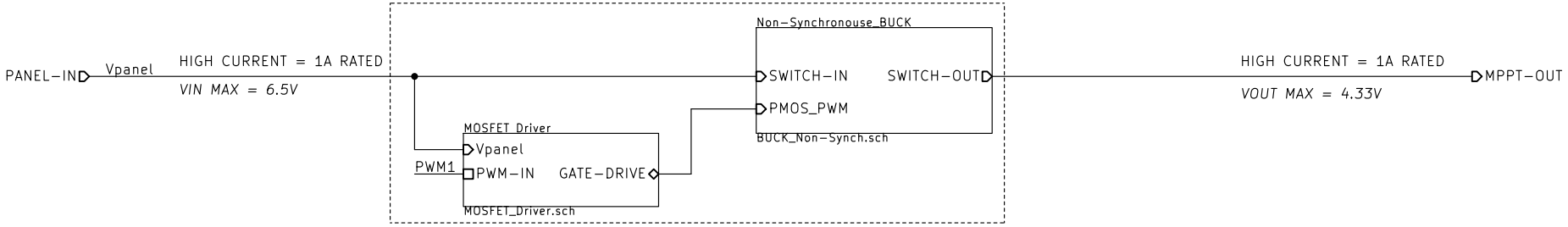
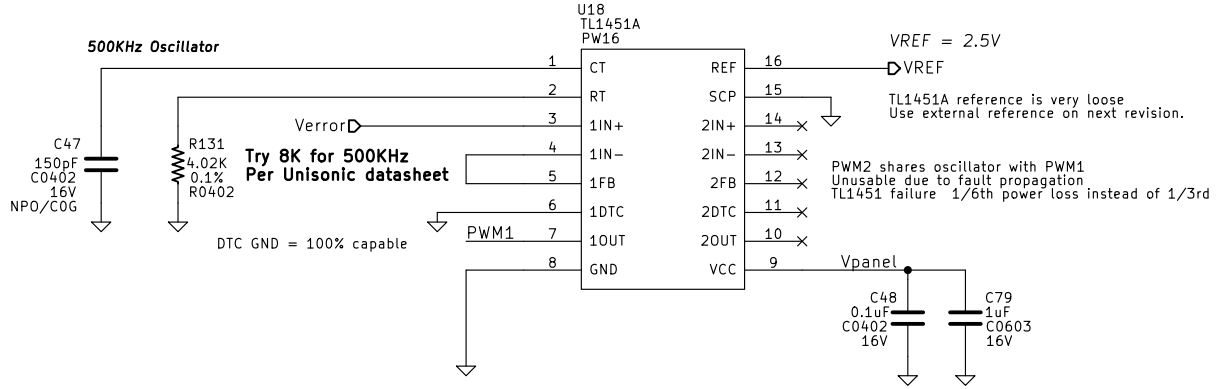
Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: MPPT_String.sch		
Sheet: /MPPT_String_Z+/		
Title: Fox−1 Maximum Power Point Tracker		
Size: A	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 33/37

Switch Mode Converter





NOTES

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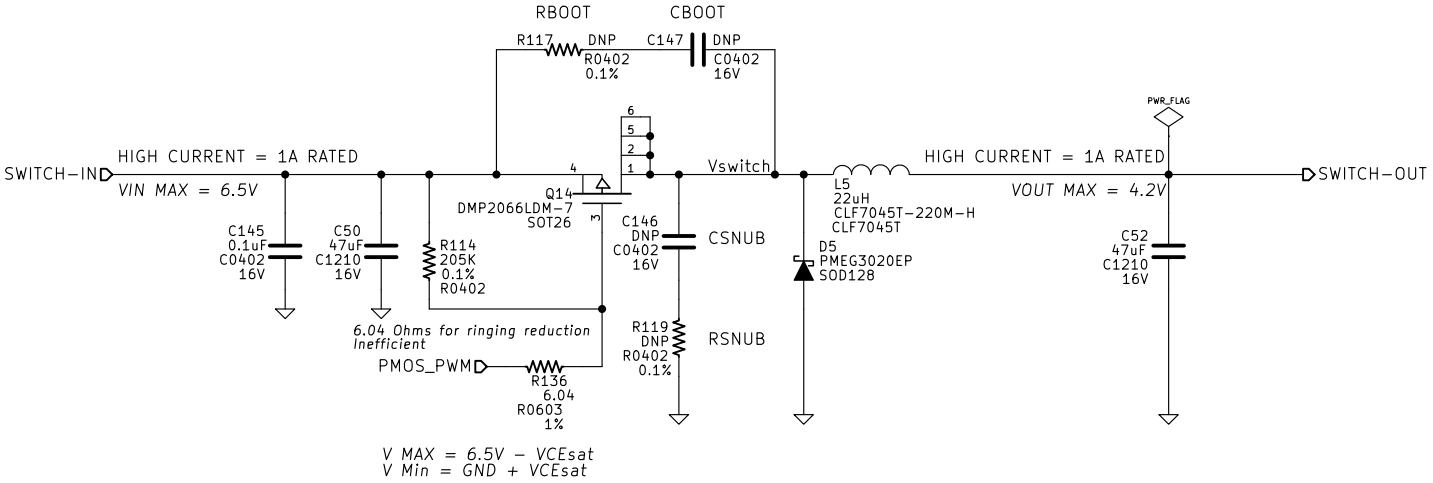
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: Control.sch		
Sheet: /MPPT_String_Z+/TL1451 Control/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 34/37

500 KHz Step-Down Buck Converter

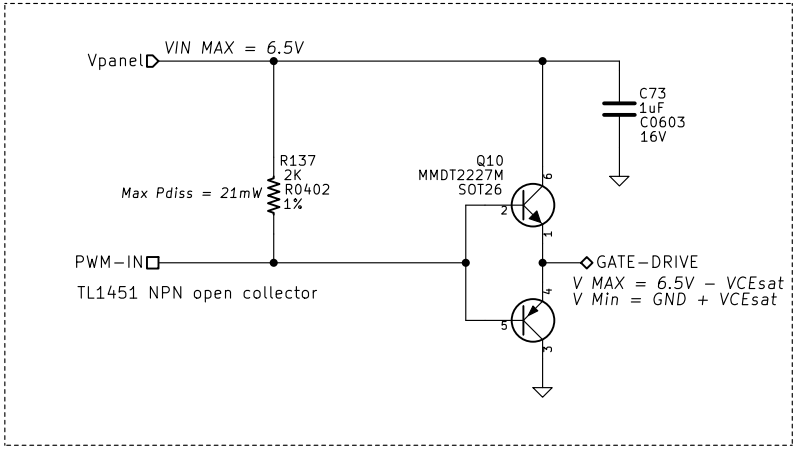


NOTES

* This MPPT implements a set-point constant voltage tracking algorithm based on panel temperature.
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* Parts not yet NASA derated.

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: BUCK_Non-Synch.sch		
Sheet: /MPPT_String_Z+/TL1451 Control/Non-Synchronouse_BUCK/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 35/37

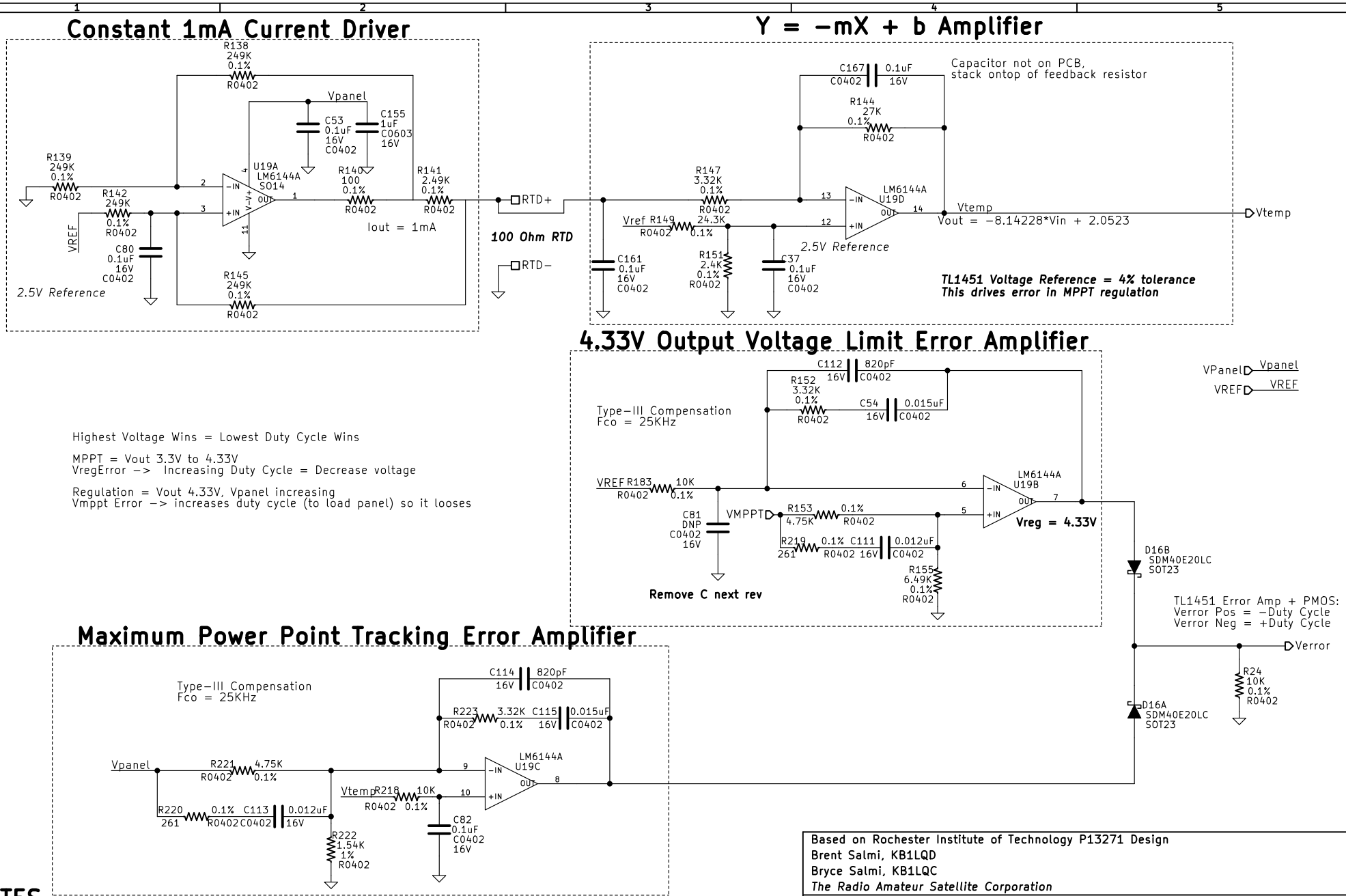
TOTEM POLE MOSFET DRIVER



NOTES

* This MPPT implements a set-point constant voltage tracking algorithm based on panel temperature.
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* Parts not yet NASA derated.

Based on Rochester Institute of Technology P13271 Design Brent Salmi, KB1LQD Bryce Salmi, KB1LQC *The Radio Amateur Satellite Corporation*		
File: MOSFET_Driver.sch Sheet: /MPPT_String_Z+/TL1451 Control/MOSFET Driver/		
Title: Fox-1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 36/37



NOTES

* This MPPT implements a set−point constant voltage tracking algorithm based on panel temperature.
* RIT MPPT Team: Brenton Salmi (KB1LQD), Bryce Salmi (KB1LQC), Ian MacKenzie (KB3OCF), Daniel Corriero.
* NASA derating taken into account, not gauranteed

Based on Rochester Institute of Technology P13271 Design		
Brent Salmi, KB1LQD		
Bryce Salmi, KB1LQC		
The Radio Amateur Satellite Corporation		
File: RTD_Measurement.sch		
Sheet: /MPPT_String_Z+/Amplifiers/		
Title: Fox−1 Maximum Power Point Tracker		
Size: A4	*Date: 25 sep 2015*	*Rev: 2*
KiCad E.D.A.		Id: 37/37